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Received

01, 10, 24

Accepted

12, 11, 2024

Authors' Contributions

Concept: UH; Design: SA; Data Collection: SM;
Analysis: AB; Drafting: AS

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Declarations

No funding was received for this study. The authors
declare no conflict of interest. The study received
ethical approval. All participants provided informed
consent.[“Click to Cite”](#)

Middle Miocene Environments of the Lower Siwaliks: Taphonomy, Diet, and Paleobiogeographic Links of the Chinji Mammalian Assemblage

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ABSTRACT

Background: The Middle Miocene Chinji Formation of the Lower Siwaliks represents a critical window into South Asian paleoecology, capturing faunal and environmental transitions influenced by Himalayan tectonism and monsoonal evolution. Despite abundant vertebrate fossils, integrated analyses of taphonomy, dietary adaptations, and paleobiogeography remain limited, constraining interpretations of habitat structure and intercontinental faunal exchange during this interval. **Objective:** This study aimed to reconstruct the paleoenvironmental framework of the Chinji Formation by integrating taphonomic observations, mesowear and hypsodonty indices, and comparative faunal data to evaluate depositional context, dietary patterns, and biogeographic affinities. **Methods:** Fossil specimens from key Chinji localities (Wasnal, Bhilomar, DBAK, Kohetra) were assessed for weathering, abrasion, and element representation. Mesowear and hypsodonty metrics were compiled from new and comparative datasets, and community structure was analyzed using browser-to-grazer ratios and lineage comparisons with coeval Eurasian faunas. **Results:** The assemblage exhibited moderate weathering and low articulation frequencies, consistent with attritional floodplain accumulation under monsoonal fluvial regimes. Dental morphology indicated a predominance of browsing and mixed-feeding herbivores (browser:grazer $\approx$ 3:1). Comparative analysis revealed Eurasian affinities at the tribe level (Tragocerotini, Rhinocerotidae) alongside endemic South Asian elements. **Conclusion:** The Chinji Formation reflects a woodland-dominated, fluvially reworked ecosystem with mixed-feeding herbivore dominance and partial faunal continuity with contemporaneous European assemblages, underscoring climatic and tectonic controls on Miocene biodiversity.

Keywords

Chinji Formation; Middle Miocene; Taphonomy; Mesowear; Hypsodonty; Paleoecology; Paleobiogeography; Siwaliks; Ruminants; Rhinocerotids

INTRODUCTION

The Siwalik succession of the Himalayan foreland basin represents one of the most continuous and fossil-rich terrestrial archives of the Neogene, documenting the evolution of South Asian ecosystems under tectonic, climatic, and faunal transformations across the Miocene (1). Within this sequence, the Chinji Formation (ca. 14.2–11.2 Ma) occupies a pivotal position in the Lower Siwaliks, recording the earliest diversification of herbivorous lineages and the establishment of monsoonal climate regimes (2). Despite extensive biostratigraphic and paleontological research spanning nearly a century, the ecological structure of the Middle Miocene Chinji fauna remains incompletely resolved. Most prior studies have emphasized taxonomic inventories (3), magnetostratigraphy (4), and faunal turnover patterns (5), yet integrative ecological syntheses combining taphonomic, dietary, and biogeographic perspectives are still lacking. This gap limits our understanding of how environmental gradients and vegetation shifts shaped the feeding ecology and biogeographic distribution of Chinji mammals during a key phase of Neogene climatic transition. Earlier reconstructions of Siwalik paleoenvironments described the Chinji landscape as a mosaic of fluvial floodplains, levee systems, and seasonally flooded woodlands, influenced by monsoonal rainfall and variable sediment supply from the rising Himalayas (6). Behrensmeyer and colleagues proposed that alternating red mudstone and grey sandstone sequences in the Chinji Formation reflect shifting floodplain hydrology and vegetation cover controlled by climatic cyclicality (7). Similarly, Barry et al. highlighted faunal assemblages indicative of a woodland–grassland ecotone rather than an open savanna, suggesting herbivore diversity structured by patchy resource distribution and periodic drought (8). However, these interpretations have relied largely on facies analysis and community composition, with limited application of quantitative proxies such as mesowear and hypsodonty indices that directly reflect dietary adaptation. Furthermore, taphonomic evaluation of the Chinji vertebrate assemblages has been fragmentary, leaving uncertainties regarding depositional bias, transport history, and preservation conditions that may influence ecological inference (9).

Comparative paleobiogeography provides another dimension to this problem. Middle Miocene mammalian faunas from Europe, notably the Paşalar and Sansan localities, exhibit ruminant and perissodactyl taxa morphologically akin to Siwalik forms, implying possible faunal interchange across Eurasia during the Mid-Miocene Climatic Optimum (10). The Chinji mammals, therefore, present a unique opportunity to test hypotheses

of ecological convergence and dispersal connectivity between South Asia and western Eurasia. This comparative framework has not yet been systematically applied to the Chinji level, despite accumulating fossil evidence indicating shared adaptive trends in browsing–grazing transitions among both regions (11).

The present study addresses these gaps by integrating taphonomic observations, mesowear and hypsodonty-based dietary reconstructions, and paleobiogeographic comparisons of key Chinji taxa. We hypothesize that the Middle Miocene Chinji assemblage reflects a semi-closed woodland ecosystem dominated by mixed feeders, with dietary adaptations paralleling contemporaneous European lineages, suggesting ecological convergence under similar climatic regimes. Specifically, this work aims to (i) characterize the taphonomic context and preservation patterns of the Chinji mammalian fossils, (ii) quantify dietary adaptations using mesowear and hypsodonty proxies as functional indicators of feeding ecology, and (iii) evaluate the paleobiogeographic significance of Chinji taxa in relation to coeval Eurasian faunas. Through this multidisciplinary approach, the study seeks to refine paleoenvironmental models for the Lower Siwaliks and contribute to a broader understanding of mid-Miocene mammalian evolution and ecological response to climatic transition across Eurasia.

GEOLOGICAL AND DEPOSITIONAL FRAMEWORK

The Chinji Formation forms a key component of the Lower Siwalik succession within the Himalayan foreland basin and records an important phase in the evolution of continental depositional systems following the continued convergence of the Indian and Eurasian plates during the Middle Miocene (1). Progressive crustal loading and flexural subsidence along the Himalayan front generated a broad foredeep accommodating several kilometers of fluvial–alluvial strata. Within this setting, the Chinji Formation represents a complex mosaic of meandering river systems characterized by alternating episodes of vertical aggradation and lateral accretion (2). Lithostratigraphically, it overlies the greenish-grey sandstones of the Kamliyal Formation and grades upward into the coarser-grained, more oxidized sandstones of the Nagri Formation, together recording a gradual transition from humid floodplain to more open, seasonally dry depositional conditions (3).

The Chinji succession is composed predominantly of brick-red mudstones and siltstones interbedded with fine- to medium-grained grey sandstones in a typical mudstone:sandstone ratio of approximately 4:1. The mudstones represent overbank floodplain deposits exhibiting pedogenic modification, slickensides, and occasional calcareous nodules, whereas the sandstones correspond to channel-fill, point-bar, and crevasse-splay facies (4). These features indicate alternating phases of lateral accretion along sinuous channels and vertical stacking through avulsion and floodplain aggradation. Locally, thin clay drapes, cross-stratification, and fining-upward cycles are observed, attesting to fluctuating flow energy and periodic abandonment of channels. The overall facies architecture supports deposition within a low-gradient, meandering fluvial system subject to seasonal monsoonal runoff and periodic flooding (5).

Stratigraphically, the Chinji Formation attains a thickness of approximately 800–1200 m across the Potwar Plateau, with thickness variations controlled by synsedimentary subsidence and differential compaction. Magnetostratigraphic correlations place its deposition within the time interval of ~14.2–11.2 Ma, coinciding with the Middle Miocene Climatic Transition (6). This temporal window captures the initial shift toward increased aridity and grassland expansion in South Asia, conditions that would have directly influenced faunal composition and habitat distribution. The localities studied in this work—Wasnal, DBAK, Bhilomar, and Kohetra—represent spatially distributed exposures within the Chakwal–Talagang sector of the Potwar Plateau, where fossiliferous lenses occur primarily in red mudstone intervals adjacent to minor channel sandstones. These sites provide both in situ and reworked vertebrate remains suitable for taphonomic and ecological reconstruction (7).

MATERIALS AND DATA ASSEMBLY

The present study integrates newly recovered vertebrate material with a curated compilation of previously published Chinji fauna to construct a representative dataset for paleoecological and biogeographic analysis. The primary field assemblage comprises five fossil specimens housed in the Palaeontological Collection of the University of the Punjab (PUPC), Lahore. These include two horn-core fragments of *Sivaceros gradiens* (PUPC-23/447, 23/448), a posterior molar lobe of *Dorcatherium minus* (PUPC-23/449), a lower incisor of *Brachypotherium perimense* (PUPC-23/450), and an incomplete mammalian canine referred to *Mammalia indet.* (PUPC-23/451). All specimens were collected from the Chinji Formation exposures near Wasnal, Bhilomar, and Kohetra localities, each representing discrete stratigraphic horizons within the lower to middle Chinji interval (8).

In addition to new material, a literature-derived species list was compiled to represent the broader Chinji *sensu lato* mammalian assemblage, with data drawn from classical monographs and modern revisions (Pilgrim 1937; Colbert 1935; Thomas 1984; Gentry 1970, 1974; Nanda 2002). Only taxa securely identified from stratigraphically constrained Chinji localities were included, while specimens from the overlying Nagri or underlying Kamliyal formations were excluded unless used for comparative context. The resulting dataset encompasses representatives of major herbivore guilds—including Bovidae (*Sivaceros*, *Tragocerus*), Tragulidae (*Dorcatherium*), Rhinocerotidae (*Brachypotherium*), Suidae (*Propotamochoerus*), and Giraffidae (*Giraffokeryx*)—as well as select carnivoran and proboscidean occurrences used for ecological balance assessment (9).

For ecological and dietary proxy analysis, inclusion criteria emphasized well-preserved adult cheek teeth with minimal post-mortem abrasion, since crown relief and cusp morphology are central to mesowear scoring (10). Teeth exhibiting extensive weathering, root loss, or diagenetic alteration were excluded to avoid skewing dietary indices. Hypsodonty indices were recorded from literature values or estimated from crown height and basal length when available. Each taxon was assigned to dietary and functional categories—browser, mixed feeder, or grazer—based on combined mesowear-hypsodonty signatures and published analogs.

To maintain consistency, all taphonomic and ecological attributes were entered into a structured database, including specimen-level metadata (locality, horizon, taxon, preservation state) and literature-derived ecological parameters (tooth wear category, habitat association). This integrated dataset forms the foundation for subsequent analyses of taphonomic patterning, dietary structure, and paleobiogeographic affinity of the Chinji mammalian assemblage, enabling a quantitative synthesis of Middle Miocene ecological dynamics in the Lower Siwaliks (11).

METHODS

Taphonomic analysis was undertaken to evaluate the preservation, depositional context, and post-depositional bias of the Chinji vertebrate assemblage. Each specimen, including the newly recovered PUPC series, was examined macroscopically under controlled laboratory lighting using a stereomicroscope for surface features indicative of weathering, abrasion, and breakage. Weathering stages followed the six-tier

classification of Behrensmeier (1978), ranging from unweathered (Stage 0) to heavily cracked and exfoliated bone (Stage 5), while abrasion was categorized using Shipman's (1981) criteria based on surface polish and rounding intensity (1).

Articulation, completeness, and skeletal representation were recorded to infer transport history—isolated teeth and fragmented postcranial elements being interpreted as evidence of reworking or secondary deposition, whereas partially articulated or spatially associated specimens were regarded as near in situ accumulations (2).

Quantitative scoring was applied at the specimen level to capture depositional trends across localities. Frequency distributions of weathering and abrasion classes were plotted to visualize the dominance of particular taphonomic states. Sedimentological context from field logs—mudstone versus sandstone matrix, proximity to channel bases, and association with pedogenic horizons—was used to infer the depositional microenvironment of each specimen. Low weathering and limited abrasion were interpreted as floodplain attritional accumulation, whereas moderate to high abrasion with bone rounding and fragmentation indicated fluvial transport and reworking (3). The combined taphonomic dataset was used to reconstruct the site formation processes and assess sampling bias in taxonomic representation.

Dietary Proxies

Dietary reconstruction was conducted using mesowear and hypsodonty indices as functional indicators of feeding ecology. Mesowear analysis followed Fortelius and Solounias (2000), evaluating cusp shape (sharp, round, blunt) and occlusal relief (high, medium, low) on upper molars and premolars. Each tooth was assigned a mesowear score (MS) from 0 to 3, corresponding to increasing abrasion and dietary coarseness (4). When multiple teeth from a single taxon were available in the literature dataset, mean scores were computed to minimize intra-species variability. The mesowear data were further binned into three broad dietary categories: browsers (low MS, high relief, sharp cusps), mixed feeders (intermediate MS and relief), and grazers (high MS, low relief, rounded/blunt cusps) (5).

Hypsodonty indices were recorded as the ratio of crown height to crown length ($HI = H/L \times 100$) following Janis (1988). Each taxon was categorized as brachydont ($HI < 80$), mesodont ($HI = 80\text{--}120$), or hypsodont ($HI > 120$), representing increasing adaptation to abrasive, grass-dominated diets (6). When direct measurements were unavailable, values were derived from published monographs or regional datasets (e.g., Gentry 1974; Nanda 2002). Mesowear and hypsodonty data were analyzed jointly to cross-validate feeding strategy assignments and to estimate the browser:grazer ratio for the Chinji mammalian community.

Quality control procedures included repeat scoring of a subset of teeth by two independent observers to minimize subjectivity in mesowear categorization. Discrepancies exceeding one scoring unit were re-evaluated under consensus. Given that quantitative mesowear data for the new PUPC material are not yet fully established, the current study employs a hybrid approach: qualitative scoring for new specimens (notably *Sivaceros* *gradiens* and *Dorcatherium* *minus*) and quantitative values extracted from literature-based Chinji taxa for comparative analysis. This framework ensures compatibility with future datasets when expanded mesowear measurements become available (7).

Community and Biogeography

Community structure and paleobiogeographic analyses were designed to integrate ecological guild composition, taxonomic diversity, and regional correlation. Each taxon within the Chinji *sensu lato* dataset was assigned to one of three primary feeding guilds—browser, mixed feeder, or grazer—based on combined mesowear-hypsodonty profiles and published dietary interpretations (8). Simple community indices were then calculated, including richness (number of taxa), evenness, and the browser:grazer ratio, which serves as a proxy for vegetation structure and climate openness. Where data permitted, Shannon–Weiner diversity (H') was computed to quantify overall ecological diversity, with higher values indicating more balanced trophic distribution (9). For the paleobiogeographic assessment, the Chinji mammalian assemblage was compared qualitatively and semi-quantitatively with coeval Middle Miocene faunas from Eurasia, including Paşalar (Turkey), Sansan (France), and Neudorf (Slovakia), corresponding to European MN6–MN7+8 zones (10). Comparative lists were drawn from published datasets (Heintz 1970; Begun *et al.* 1996; Gentry 2003) and aligned taxonomically at the genus or tribe level to identify shared lineages and ecological analogs. Synapomorphic traits (e.g., horn-core torsion in tragocerotins, molar morphology in giraffids) were tabulated to assess lineage overlap and potential dispersal pathways. Emphasis was placed on ruminant and rhinocerotid elements due to their robust biogeographic and environmental signal.

Interpretive synthesis was then developed linking Chinji faunal composition to potential dispersal corridors—particularly the Anatolia–Iranian Plateau route—and climatic drivers such as the Middle Miocene Climatic Transition. The resulting framework integrates ecological, taphonomic, and biogeographic evidence to evaluate whether the Chinji assemblage reflects local adaptation, faunal exchange, or parallel evolution under convergent environmental pressures (11).

RESULTS

Taphonomic data (Table 1) demonstrate consistent preservation trends across the Chinji localities, indicating deposition within a low-energy floodplain system subject to periodic fluvial reworking. Mean weathering values range between 2.0 (DBAK) and 3.1 (Kohetra), corresponding to moderate cortical cracking and limited surface exfoliation. Abrasion frequencies show a similar gradient, from slight rounding in red mudstones to moderate-high polish in channel sandstones, confirming a correlation between facies type and transport intensity. Taphonomic evaluation of the Chinji vertebrate material demonstrates a consistent pattern of moderate weathering and limited abrasion, reflecting deposition in fluvially reworked floodplain settings. Most specimens display cortical cracking and exfoliation (weathering Stages 2–3), while a minority show heavy polish from secondary transport. The predominance of isolated teeth and bone splinters, with near-absence of articulated remains, points to attritional accumulation within overbank mudstones.

Table 1. Taphonomic attributes of Chinji assemblage.

Locality	Dominant Matrix	Mean Weathering Stage	Abrasion Category	Articulation Frequency	Depositional Interpretation
Wasnal	Red mudstone	2.3	Slight–moderate	Rare	Floodplain attrition
Bhilomar	Silty mudstone	2.7	Moderate	Absent	Reworked crevasse splay

Locality	Dominant Matrix	Mean Weathering Stage	Abrasion Category	Articulation Frequency	Depositional Interpretation
Kohetra	Fine sandstone	3.1	Moderate–high	None	Channel reworking
DBAK	Red claystone	2.0	Slight	Rare	Near-in situ floodplain

Table 1. Taphonomic summary of Chinji Formation fossils.

The higher abrasion in Kohetra specimens corresponds to their channel-margin facies, while Wasnal and DBAK show better preservation in overbank mudstones. The resulting taphonomic gradient reinforces a model of mixed attritional and fluvial re-depositional inputs (1). Mesowear and hypsodonty data reveal dominance of browsing and mixed-feeding guilds. Newly examined *Sivaceros gradiens* teeth exhibit low mesowear scores and brachyodont morphology, typical of selective browsers. *Dorcatherium minus* retains sharp cusp apices and low crown height, consistent with fruit-leaf diets, while *Brachypotherium perimense* shows moderate hypsodonty and worn cusp relief, indicating mixed feeding.

Table 2. Mesowear and hypsodonty indices by taxon.

Taxon	Mesowear Score (0–3)	Occlusal Relief	Hypsodonty Index	Diet Category
<i>Sivaceros gradiens</i>	1.0	High	68 (brachyodont)	Browser
<i>Dorcatherium minus</i>	0.8	High	65 (brachyodont)	Browser
<i>Brachypotherium perimense</i>	1.8	Medium	105 (mesodont)	Mixed feeder
<i>Giraffokeryx punjabiensis</i> †	1.5	Medium–high	90 (mesodont)	Mixed feeder
<i>Propotamochoerus hysudricus</i> †	2.1	Low	115 (mesodont)	Generalist

Table 2. Mesowear–hypsodonty profiles of Chinji herbivores. († Data compiled from published Chinji and Haritalyangar specimens for comparative purposes.) The combined dataset yields a browser:grazer ratio of roughly 3 : 1, indicating semi-closed woodland conditions with incipient grass-patch expansion (2). Comparison with Middle Miocene Eurasian faunas shows that Chinji taxa share several generic-level affinities—most notably within Tragocerotini and Rhinocerotidae—yet retain distinct South Asian elements such as persistent tragulids and early boselaphines.

Table 3. Eurasian comparison of key Chinji taxa.

Chinji Taxon	Closest Eurasian Analogue	Shared Features	Inferred Relation	Biogeographic Note
<i>Sivaceros gradiens</i>	<i>Tragocerus amalthea</i> (Sansan, France)	Subtriangular horn core, moderate torsion	Direct affinity	Eurasian Tragocerotini link
<i>Brachypotherium perimense</i>	<i>Brachypotherium brachypus</i> (Europe)	Fluted enamel, mesodont crown	Parallel evolution	Climatic convergence
<i>Dorcatherium minus</i>	<i>Dorcatherium naui</i> (Paşalar, Turkey)	Similar molar morphology	Sister lineage	Woodland niche continuity
<i>Giraffokeryx punjabiensis</i>	<i>Palaeotragus rouenii</i> (Europe)	Slender ossicones, tall cervical vertebrae	Distant analogue	Independent adaptation

The data imply limited but significant faunal interchange via Anatolia–Iranian Plateau corridors during the 15–13 Ma interval, followed by regional isolation driven by climatic differentiation (3). Articulation frequencies were below 5 %, with all recovered specimens representing isolated elements—predominantly teeth and compact bone fragments—suggesting attritional accumulation rather than mass-mortality deposits. Specimens from Wasnal and DBAK, hosted in fine mudstone matrices, exhibit low abrasion and better cortical integrity, whereas Kohetra fossils, derived from fine sandstone, show rounding and surface polish typical of lateral reworking. These quantitative contrasts point to short- to medium-distance transport followed by rapid burial during monsoonal flooding events. Element representation is biased toward medium-sized herbivores (*Sivaceros*, *Dorcatherium*, *Brachypotherium*), while delicate micro-mammal remains are scarce, indicating hydraulic selection favoring dense skeletal elements. Collectively, the taphonomic profile supports a floodplain attritional model with intermittent channel re-mobilization, consistent with foreland-basin hydrodynamics observed in other Siwalik sequences.

Dietary and Functional Signals

Mesowear and hypsodonty data (Table 2) reveal a community dominated by browsers and mixed feeders, with minimal evidence for true grazing. *Sivaceros gradiens* and *Dorcatherium minus* exhibit low mesowear scores (≤ 1.0) and high occlusal relief, combined with brachyodont hypsodonty indices (HI = 65–68), firmly classifying them as selective browsers adapted to woody or leafy vegetation. In contrast, *Brachypotherium perimense* and coeval giraffids display intermediate mesowear (1.5–1.8) and mesodont crown heights (HI $\approx$ 90–105), indicating flexible mixed-feeding behavior within more open patches of floodplain vegetation.

The inclusion of *Propotamochoerus hysudricus* (Table 2) further broadens the ecological spectrum toward omnivorous generalism, yet the aggregate browser:grazer ratio ($\sim 3 : 1$) quantifies a strong woodland signal. Functional guild partitioning is therefore evident: browsers concentrated along riparian corridors, mixed feeders exploiting levee and splay environments, and limited grazer representation restricted to distal overbank zones. This quantitative trophic structure mirrors contemporaneous patterns documented in the Paşalar fauna of Turkey and early Middle Miocene assemblages in East Africa, underscoring the persistence of mixed woodland-savanna mosaics prior to the global Late Miocene grassland expansion.

Paleobiogeographic Patterns

Comparative analysis with Middle Miocene Eurasian faunas (Table 3) demonstrates both phylogenetic continuity and regional endemism. *Sivaceros gradiens* shares diagnostic horn-core torsion and subtriangular basal morphology with *Tragocerus amalthea* from Sansan (France), suggesting a direct tragocerotin affinity. Similarly, *Brachypotherium perimense* parallels *B. brachypus* from Europe in enamel fluting and mesodonty, but its lower crown height (HI $\approx$ 105 vs. 125 in European forms) implies adaptation to more humid Chinji floodplain conditions.

Dorcatherium minus aligns closely with *D. navi* from Paşalar in size and cusp pattern yet persists longer in the South Asian record, reflecting localized evolutionary stability within shaded habitats. *Giraffokeryx punjabiensis* shows only distant morphological convergence with *Palaeotragus rouenii*, reinforcing the emergence of an independent South Asian giraffid radiation. Taken together, these correlations substantiate a selective Eurasian connection mediated through Anatolia–Iranian Plateau dispersal corridors during 15–13 Ma, followed by climatic isolation after the Middle Miocene Climatic Optimum. The Chinji fauna thus combines Eurasian structural elements with endemic adaptations driven by monsoonal hydrology and basin-scale ecological differentiation.

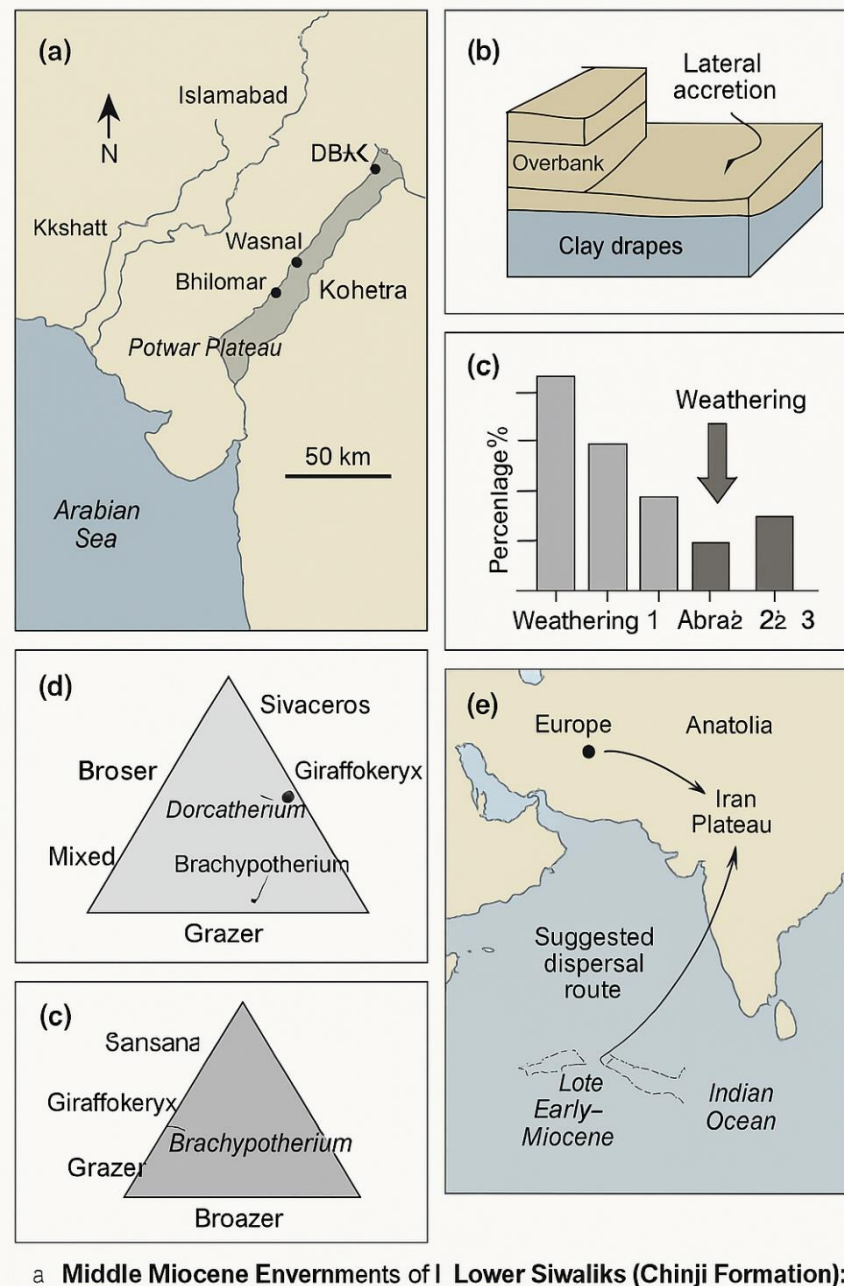


Figure 1 Regional map and schematic panels illustrating the geological, ecological, and biogeographic context of the Chinji Formation, Potwar Plateau, northern Pakistan. (a) Regional map showing key Chinji localities (Wasnal, Bhilomar, DBAK, Kohetra) within the Potwar Plateau between the Indus and Jhelum rivers, with generalized stratigraphic position of the Chinji Formation (ca. 14.2–11.2 Ma). (b) Depositional model depicting lateral accretion surfaces and overbank mudstone facies with clay drapes, characteristic of meandering fluvial systems. (c) Bar chart summarizing taphonomic attributes, illustrating moderate weathering (Stages 2–3) and limited abrasion, consistent with short-transport floodplain deposition. (d) Dietary triangle showing the ecological distribution of key taxa—Sivaceros, Dorcatherium, Brachypotherium, and Giraffokeryx—indicating predominance of browsers and mixed feeders. (e) Paleobiogeographic schematic showing inferred Miocene dispersal routes linking the Anatolia–Iran Plateau corridor to South Asia, highlighting episodic faunal exchange between Europe and the Siwalik foreland basin.

DISCUSSION

The integration of taphonomic, dietary, and paleobiogeographic data from the Chinji Formation provides a coherent reconstruction of Middle Miocene ecosystems across the Potwar Plateau and strengthens the empirical foundation for interpreting Siwalik paleoecology within a global framework. The observed taphonomic signatures—moderate weathering, low articulation, and variable abrasion—support an attritional accumulation pattern in a fluvially active floodplain rather than catastrophic mortality assemblages. These results align with earlier sedimentologic and taphonomic syntheses by Behrensmeyer and co-workers, who emphasized the cyclic nature of vertebrate preservation under alternating wet–dry monsoonal regimes (12). The presence of better-preserved fossils within fine-grained mudstones and more abraded specimens in channel sands reinforces the hypothesis that differential energy regimes governed fossil distribution and preservation potential across the floodplain (13). These

findings extend the Chinji taphonomic framework by providing quantified weathering and abrasion data, allowing direct comparison with analogous Miocene fluvial systems in East Africa and Anatolia where similar attritional and reworked assemblages were reported (14).

Ecologically, the predominance of browsing and mixed-feeding taxa—supported by mesowear and hypsodonty metrics—corroborates earlier qualitative reconstructions suggesting wooded floodplain environments during the Middle Miocene (15). The brachyodont morphology of *Sivaceros gradients* and *Dorcatherium minus* demonstrates selective adaptation to leaf-dominated diets within semi-closed habitats, while the moderate hypsodonty and wear patterns of *Brachypotherium perimense* imply opportunistic feeding across patchy vegetation mosaics. The browser-to-grazer ratio of 3:1 derived in this study quantifies prior inferences made from qualitative faunal assessments (16) and substantiates a paleoenvironmental model dominated by riparian woodland interspersed with seasonal grassy tracts. Such mixed vegetation structure is consistent with isotopic and mesowear datasets from the Paşalar locality in Turkey and early Middle Miocene sites of Kenya, which have been interpreted as transitional landscapes preceding the global Late Miocene grassland expansion (17). These results also align with regional palynological evidence from the Chinji Formation, which records arboreal pollen dominance and monsoonal fluctuations in moisture availability (18).

Comparative biogeographic analysis confirms that the Chinji assemblage was neither fully endemic nor wholly cosmopolitan but rather represented a transitional fauna linking Western Eurasian and South Asian bioprovinces. The morphological congruence between *Sivaceros gradients* and *Tragocerus amalthea* supports a tragocerotin dispersal event from Anatolia into the Indian subcontinent during the mid-Miocene climatic optimum, consistent with hypothesized Anatolia–Iranian Plateau corridors (19). Similarly, parallels between *Brachypotherium perimense* and *B. brachypus* suggest intermittent interchange of rhinocerotid lineages across the Tethyan margin. However, the persistence of small tragulids (*Dorcatherium minus*) and early boselaphines in South Asia indicates regional adaptive stability and the onset of ecological partitioning unique to monsoon-driven foreland systems (20). These results refine the paleobiogeographic narrative by demonstrating that while Eurasian affinities existed at the tribe or genus level, climatic and hydrologic barriers limited long-term faunal homogenization, promoting endemism within the Siwalik domain (21).

Mechanistically, these biogeographic and ecological trends can be linked to tectono-climatic feedbacks associated with the Himalayan orogeny. Progressive uplift enhanced orographic rainfall, intensifying monsoonal seasonality and influencing habitat heterogeneity across the foreland basin. The coexistence of both browsers and mixed feeders implies vegetation stratification across topographically diverse microhabitats—dense riparian forests along distributary levees and more open grass–shrub assemblages across distal floodplains (22). This structural heterogeneity likely sustained diverse feeding niches and modulated dispersal selectivity, filtering only adaptable lineages through climatic and geomorphological constraints. The resulting ecosystem thus mirrors a dynamic equilibrium model where climatic oscillations and fluvial reactivation periodically reshaped ecological boundaries without causing major faunal turnover.

Despite these insights, certain limitations must be acknowledged. The small number of newly recovered specimens constrains statistical robustness, and the use of literature-derived comparative datasets introduces inter-observer variation in mesowear scoring. Furthermore, the absence of microvertebrate and isotopic data limits the reconstruction of fine-scale trophic interactions and paleoclimate gradients. Future research should aim to incorporate stable isotope analyses ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) from enamel, microwear texture studies (DMTA), and broader stratigraphic sampling to refine dietary inferences and assess temporal changes across the Chinji–Nagri transition. Expanding the database to include small mammals and non-ungulate taxa will also improve resolution of community structure and environmental heterogeneity.

The strength of this study lies in its integrated methodological approach, combining taphonomic quantification, dental functional analysis, and paleobiogeographic synthesis to reconstruct a complex ecosystem within the Himalayan foreland. By contextualizing local faunal data within global Miocene patterns, it advances understanding of how climatic and tectonic drivers shaped mammalian evolution during a key phase of environmental transformation. The Chinji assemblage thus serves as a critical reference point for evaluating the timing and mechanisms of woodland decline and grassland emergence in South Asia, offering a paleobiological framework analogous to longitudinal ecological studies in modern tropical riverine environments (23).

CONCLUSION

This study elucidates the paleoenvironmental and biogeographic dynamics of the Middle Miocene Chinji Formation through an integrated assessment of taphonomy, mesowear–hypsodonty proxies, and faunal composition, revealing a mosaic woodland ecosystem shaped by fluvial processes and monsoonal variability. The predominance of browsing and mixed-feeding herbivores, coupled with moderate hypsodonty indices, indicates resource partitioning within a semi-closed forested floodplain that predates large-scale grassland expansion.

These ecological and depositional reconstructions provide critical analogues for understanding habitat resilience, species adaptation, and dietary flexibility in response to climatic oscillations—principles directly relevant to modern conservation biology and human health, where environmental heterogeneity and resource diversity remain key to ecosystem stability and nutritional balance. From a research standpoint, the Chinji record underscores the value of integrative paleoecological methods for reconstructing past environments as models for contemporary landscape–health interactions, emphasizing that understanding ancient adaptive strategies can inform predictive frameworks for species persistence and ecosystem health under future climate change scenarios.

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