Tropical Natural History 24 (2024): 239-245

Paleopalynofloras of the Eocene in South Asia

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Received: 9 June 2024; Accepted: 24 November 2024

ABSTRACT. – The current study focuses on the previous research on paleopalynology of existing plants from different regions of the Eocene strata of South Asia. This study was conducted for the first time in the study area to highlight the distributions, identifications, and abundance of the floral paleopalynological record of the Eocene in South Asia. The study attempts to describe plant evolution, reconstructions of past climate change, and the effects of these changes on plant communities over time in the study area. The vegetation of the study area during the depositional period was better predicted by the existence of fossil flora. The proposed work yields data on the dominant fossil plant taxa that existed in South Asia over megaannum–including trees, shrubs, herbs, bryophytes and aquatic macrophytes. Results of this work promise to yield novel insights into the synergistic effects of climate change and paleoecology and evolution of plant communities. The data proved useful for establishing links with other branches of sciences, including archaeology, geology, plant ecology and environmental science. The current study aimed to describe phylogeny, reconstructions of past climate change and its effects on plant communities in the Eocene period of south Asia.

KEYWORDS: Eocene, paleopalynology, South Asia, vegetation, climate

INTRODUCTION

The Eocene epoch represents a critical period in Earth's history, characterized by significant biological, geological, and climatic changes (Berggren et al., 1998). This epoch is mainly important for the emergence and diversification of many modern plant and animal groups, constructing a main point for paleontological study (Lindow and Dyke, 2006). In South Asia, the Eocene is marked by the collision of the Indian subcontinent with the Eurasian plate, leading to insightful changes in the region's biodiversity and ecology (Bibi and Métais, 2016). The global paleogeographic map of the Eocene was shown in figure 1. This tectonic occurrence not only influenced the geological setting but also played a key role in shaping the flora and fauna of the region, as evidenced by the fossil records that have been discovered (Su et al., 2018; Liu et al., 2017). Paleopalynology, the study of fossilized pollen and spores, serves as a dynamic tool for reconstructing past environments and understanding the evolutionary history of plant life during the Eocene. The fossilized remains of pollen grains and spores allow researchers to gather the composition of ancient ecosystems, track changes in flora over time, and understand the biogeographic patterns that emerged because of climatic changes and continental movements (Liu et al., 2015; Li et al., 2016; Maslova, 2023).

Paleopalynology in South Asia is not just significant for identifying ancient plant species but also for understanding how ecosystems changed and shaped the evolution of different plants over time (Ahmad et al., 2023). For example, the occurrence of specific pollen types can show the climatic conditions of the time, such as temperature and humidity levels, which in turn affect the distribution of plant species (Dahl et al., 2013). This understanding is essential for reconstructing the paleoclimate of the Eocene and evaluating how these prehistoric ecosystems responded to environmental changes (Chen and Manchester, 2015; Marivaux et al., 2023). In South Asia, palynofloras of the Eocene show arrangements of plant life, containing angiosperms, gymnosperms, and ferns, which grow well in a variety of habitats ranging from subtropical forests to wetlands (Singh et al., 2011). The fossil record suggests that the region was once home to and had rich varieties of plants,

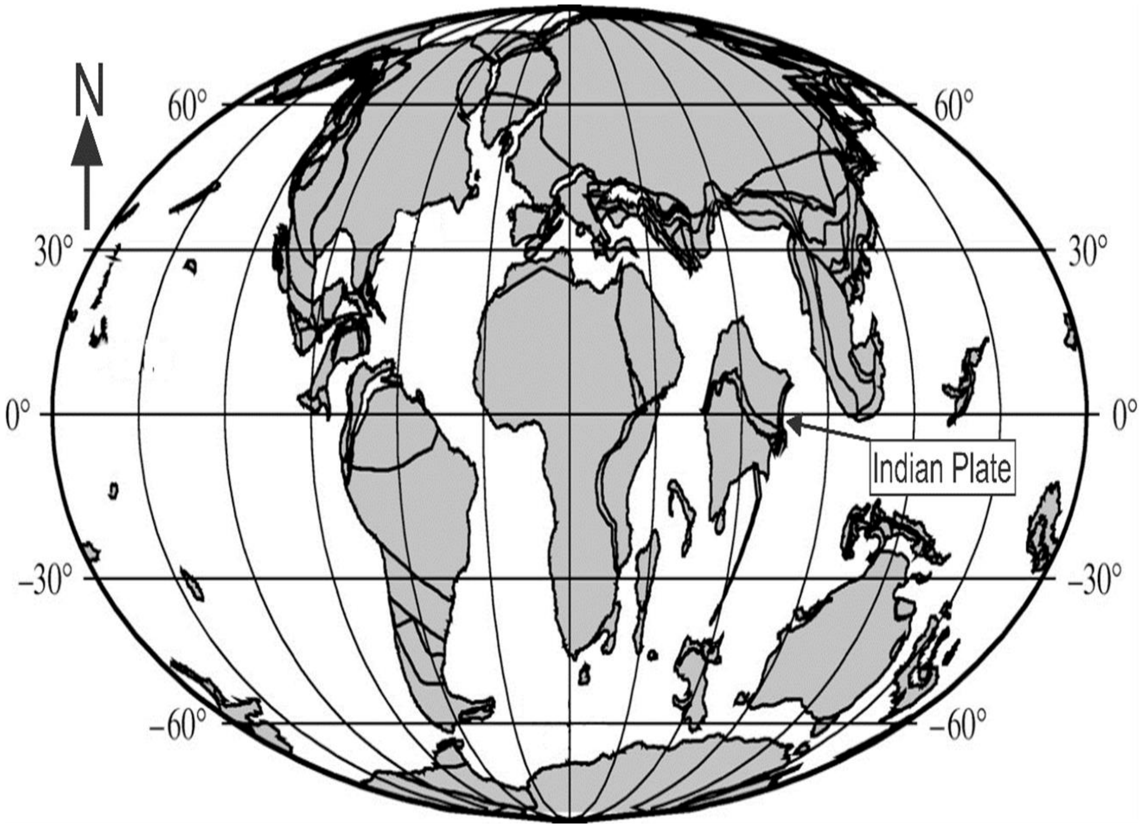

FIGURE 1. Eocene global paleogeographic map of the world showing positions of various tectonic plates (Zachos et al., 2007).

which provided support for different plants in the ecosystem (Eberle and Greenwood, 2012). The relationship between plants and animals is crucial for understanding the evolutionary history of birds, mammals, and other taxa that emerged during the Eocene (Marivaux et al., 2005; Averianov et al., 2016).

Furthermore, the Eocene epoch was a significant period of mammalian evolution and the emergence of key groups such as primates and ungulates (Simpson, 1937). Fossils from South Asia show that it was a hotspot for mammal evolution, influenced by tectonic and climate changes (Marivaux et al., 2023; Marivaux et al., 2005). Early primate fossils found in Pakistan highlight that South Asia played a crucial role in primate evolution (Marivaux et al., 2023). The collision between the Indian subcontinent and Asia allowed the species to spread in the continents, constructing new ecological niches (Liu et al., 2017; Su et al., 2018). Palynological studies from the Eocene offer insights into plant and animal evolution, which helps us to understand modern biodiversity and predict responses to climate change (Liu et al., 2015; Li et al., 2016; Maslova, 2023).

Geological Context of the Eocene Stratigraphy in South Asia

The Eocene epoch was a crucial period in the geological history of South Asia, characterized by dynamic tectonic activity, climatic changes, and various biotic interactions (Tardif et al., 2020). During this time the tectonic activity, including the collision between the Indian and Eurasian plates, started the raise of the Himalayas and the Tibetan Plateau (Dobretsov et al., 1996). This geological incident significantly affected the area's topography, climate, and biodiversity (Manish and Pandit, 2018). The formation of sedimentary basins, for example the Cambay Shale in western India, offers valuable stratigraphic records that help to understand the biogeographic and evolutionary history of the region (Verma and Singh, 2024). The fossil record, comprising early Eocene tapiromorphs, offers valuable insights into mammalian evolution in Asia (Su et al., 2018; Kapur and Bajpai, 2015). The stratigraphic column of different formations in Pakistan were shown in figure 2.

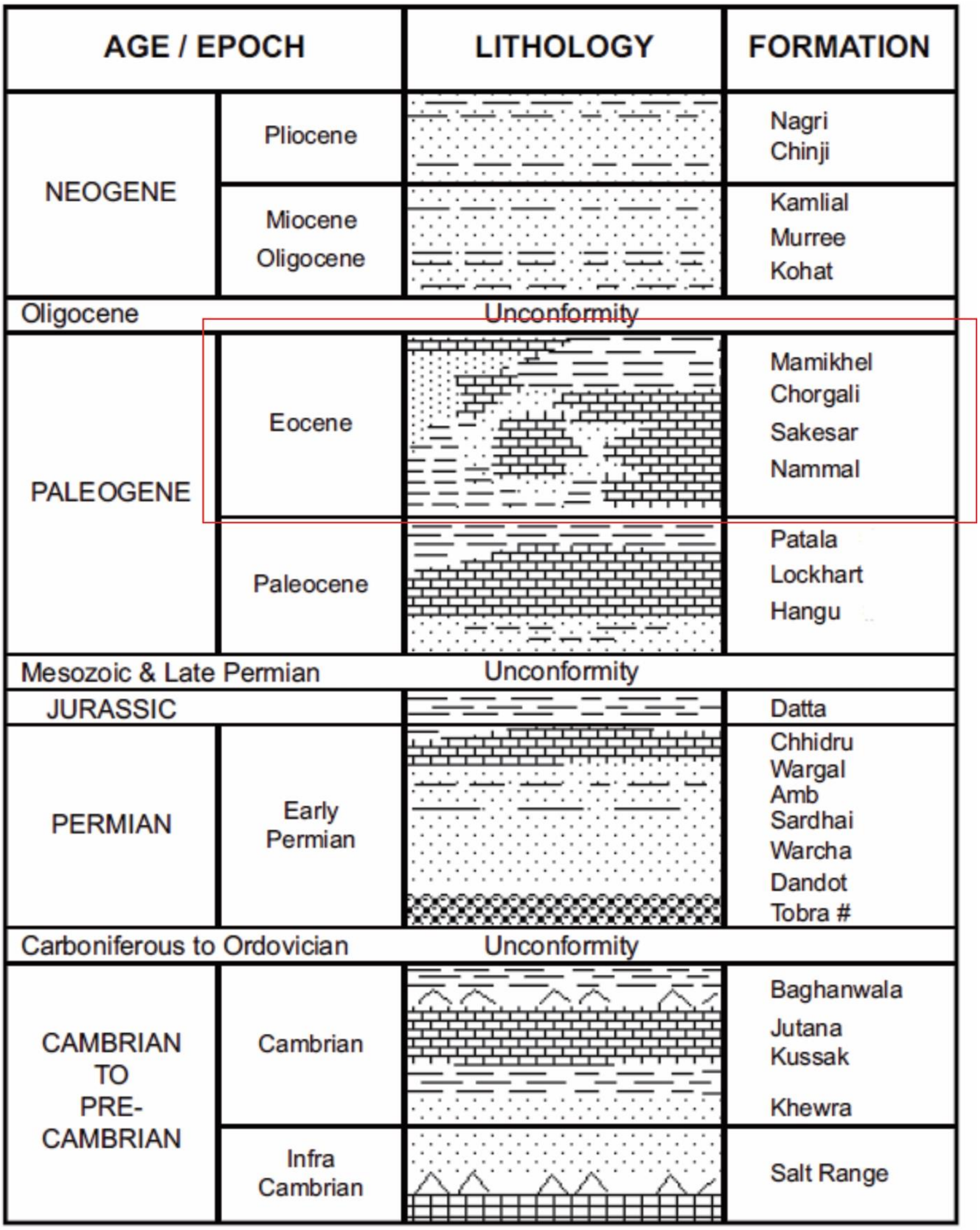

FIGURE 2. Lithological log of the Eocene strata in the Potwar Plateau, Pakistan (Wandrey et al., 2004).

During the Eocene, the climatic conditions were marked by a warm greenhouse climate, which sustained various ecosystems (Huber and Caballero, 2011). This study specifies that South Asia experienced stronger monsoonal conditions, which are marked in the leaf structures of fossilized vegetation (Spicer et al., 2016). Fossil leaf records from this period show architectural characteristics like those found in modern monsoon climates, indicating that a well-developed monsoon system existed during the Eocene (Spicer et al., 2016). The conditions were suitable for the growing of different flora, as proved by fossil deposits throughout the study area.

Paleobotanical discoveries in South Asia from the Eocene stratigraphy are further highlighting that they have rich biodiversity (He et al., 2022). The fossil records belong to different families, such as Menispermaceae and Fagaceae, indicate extensive distributions in tropical and subtropical environments during this period (Liu et al., 2015; Meng et al., 2019). The occurrence of these families of plants in the fossil evidence highlights South Asia's role as a midpoint for plant diversification and biogeographic connections (Li and Feng, 2015). In addition, the fossil record suggests major biotic exchanges between South Asia, Africa, and Southeast Asia to the contributing of diverse floral and faunal composition to the regions (Bibi and Métais, 2016; Peng et al., 2021). Biotic exchanges throughout the Eocene played a vital role in the evolution of several taxa (Li et al., 2013). Fossil investigation indicates that ancestral South Asian eosimiids, early primates, distributed from the Tethys Sea to Afro-Arabia during the middle Eocene, suggesting that South Asia was important to the early evolutionary history of anthropoid primates (Marivaux et al., 2005; Marivaux et al., 2023). Furthermore, research on the range evolution of freshwater crabs provides additional evidence of direct Eocene biotic exchanges between India and Southeast Asia, contributing to the biodiversity seen in present-day South and Southeast Asia (Klaus et al., 2010).

In South Asia, Eocene basins, such as the Himalayan foreland basin, Indus Basin, and the Siwalik Hills, have provided critical palynological data that reveal important insights into past plant diversity and climatic conditions (Gaur, 2016; Morley and Morley, 2022). Palynological records from these basins suggest that megathermal rainforests dominated the region during this period, reflecting a warm and humid climate (Klaus et al., 2010). Also, these basins reveal biogeographic connections between South Asia and Southeast Asia, with fossil records indicating shared plant taxa across these regions during the Eocene (Spicer et al., 2016). This highlights the significance of these Eocene deposits for understanding the evolutionary dynamics and paleoclimate of South Asia.

Pollen and Spore Assemblages of the Eocene in South Asia

The investigation of pollen and spore assemblages from this epoch shows a rich diversity of vegetation types and ecological perspectives that not only describe the region but also allow for comparisons with global records (Connor et al., 2021; Ahmad et al. 2023). Particularly, studies of lignite deposits in Gujarat have discovered various assemblages of dinoflagellate cysts, pollen, and spores, showing a warm paleotropical climate during the Early Eocene (Uddandam, 2023). This climatic condition raised the growth of tropical angiosperms, with specific pollen types, such as those from the Myricaceae family, suggesting the occurrence of swampy environments helpful to humid-adapted plant species (Harrington, 2008). The ecological settings of these assemblages, mainly from the Kutch Basin, further explain the warm and humid climate that sustained the propagation of tropical angiosperms and larger benthic foraminifera, aligning with discoveries from other parts of Asia that point out the formation of monsoon systems during the Eocene (Spicer et al., 2016; Khanolkar et al., 2017).

The ecological implications of these findings extend beyond simple taxonomic identification; they provide insights into the evolutionary pressures and environmental changes that influenced the development of flora and fauna during the Eocene (Bhatia et al., 2021; Couvreur et al., 2021). The fossil discoveries indicate that the Eocene was marked by significant climatic changes, influencing the distribution and diversity of plant species. For example, the mid-Eocene greenhouse warming had insightful effects on the floras of southern continents, including South Asia, key to changes in vegetation types and the appearance of new taxa (Fernández et al., 2021). The presence of taxa such as *Artemisia* and *Chenopodipollis*, which became more prominent in the late Eocene, reveals changing ecological conditions perhaps linked to the beginning of acidification (Long et al., 2011). Additionally, comparative studies with global records show that the Eocene flora of South Asia shares resemblances with other regions, mainly in terms of the types of vegetation that grow during this epoch, highlighting wider biogeographic links (Halbwachs et al., 2022).

The relationship between vegetation, climate, and faunal evolution during the Eocene was further explained by discoveries from lignite mines in western India, where several microfossil collections have been analyzed to gather paleoenvironmental conditions (Khanolkar and Sharma, 2019). The existence of various pollen types, along with foraminifera and dinoflagellates, suggests a complex relationship of ecological factors that influenced the development of Eocene ecosystems (Prasad et al., 2018). This complication is reflected in the global context, where similar arrangements of vegetation change have been documented in response to climatic changes. The variation of rodent faunas in South Asia during this time, showing unique characteristics compared to their European and African counterparts highlights the regions distinct ecological evolution (Li et al., 2022). Such patterns are critical for reconstructing the paleogeographic history of South Asia and its connections to other regions, represented by the distribution of taxa like Nageia, which initiated in northeastern Asia and spread to South China during the Eocene (Liu et al., 2015).

Challenges and Future Directions in Eocene Paleopalynology

The research of Eocene paleopalynology in South Asia has made significant progress in understanding the region's ancient ecosystems and climatic conditions. However, several challenges and gaps in the existing palynological data inhibit a broad understanding of the Eocene flora and its implications for paleoclimate and biogeography. One of the main challenges is the limited geographic coverage of palynological studies. Whereas the areas such as the Indus Basin and the Himalayan foreland have been comprehensively explored, other regions, particularly the Bengal Basin and parts of northeastern India, remain unexplored. This lack of coverage restricts the ability to draw comprehensive conclusions about regional floral diversity and climatic conditions during the Eocene (Liu et al., 2020; Salman et al., 2021).

Another significant challenge is the lack of stratigraphic records in current research, which frequently focuses on specific stratigraphic units. This leads to a fragmented understanding of palynological assemblages across different formations i.e Maoming Basin in South China has produced rich palynological data; similar comprehensive studies in South Asia are missing (Spicer et al., 2016). Furthermore, the insufficient taxonomic resolution of palynological data often complicates important ecological and evolutionary patterns. Many studies report palynological assemblages at a wide-ranging taxonomic level, which may overlook significant species-level diversity (Beal et al., 2021; Dinda, 2014). This gap in taxonomic resolution restricts the ability to evaluate the ecological roles of specific plant taxa and their responses to climatic changes (Ahmad et al. 2024).

The under implementation of modern techniques in palynological studies offer another barrier to advancing the field. Although advancements such as molecular analysis and high-resolution imaging, many studies in South Asia still rely on traditional methods of palynological analysis. This support may inhibit the correctness and comprehensiveness of palynological data. For instance, the application of molecular techniques could improve the understanding of evolutionary relationships among Eocene plant taxa and provide insights into their biogeographic patterns (Tang et al., 2019; Lukacs, 2011). Furthermore, there is a persistent need for more integrated methodologies that combine palynological data with other geological and paleoclimatic data. Many studies focus exclusively on palynology without considering the broader geological context, including geochemistry and sedimentology. Integrating these corrections could yield a more inclusive understanding of the Eocene ecosystems in South Asia and their responses to tectonic and climatic changes (Benedict et al., 2018; Kang et al., 2022).

To address these challenges and gaps, future research in Eocene paleopalynology in South Asia should focus on expanding geographic coverage, conducting comprehensive stratigraphic studies, enhancing taxonomic resolution, integrating multidisciplinary approaches, and utilizing advanced technologies. Conducting palynological studies in underrepresented regions, such as the Bengal Basin and northeastern India, will enhance the geographic scope of Eocene palynology. Using modern techniques such as Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) can significantly improve the taxonomic resolution of palynological data (Putten et al., 2012; Aradhya et al., 2017). Encouraging interdisciplinary collaborations that combine palynology with sedimentology, geochemistry and paleoclimatology can provide a more comprehensive understanding of Eocene ecosystems. While implementing advanced imaging and molecular techniques will enhance the accuracy and depth of palynological analyses, helping with better insights into the evolutionary history of Eocene floras in South Asia (Vornlocher et al., 2021; Rahaman et al., 2020).

CONCLUSION AND RECOMMENDATIONS

Paleopalynological records of fossil plants from Eocene strata provide vegetational history about the climatic changes occurring in the Eocene strata. Variability in the family and genera wise plants based on elevational gradient helps in providing information about the past climate of the areas. Findings of the present study suggest that lower vascular plants dominate the Eocene strata. Further studies will be needed to understand its relationships with other strata and vegetations evolutionary relationships. This study provides information about systematic linkage of species and realizes the importance of ancestors. Paleobotanical records play an important role in the origin of South Asia's modern flora with their correlation between vegetation and climate. Based on these data, it has been concluded that many taxa originated in the study area and are considered important to study the origin and development of lower and higher vascular plants.

ACKNOWLEDGMENTS

This work was supported by Western Light Project of CAS (xbzg zdsys 202204)), NSFC (42161144012).

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