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Warm and humid Trans-Himalaya during the late Miocene: plant fossil evidence

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Abstract

Neogene fossil records from the Indus Basin sedimentary rocks (IBSR), deposited in the Indus Tsangpo Suture Zone (ITSZ), are very rare, but are important to understand the history of plant diversity and paleoclimate in the Himalaya. We report fossil wood ascribed to *Ebenoxylon siwalicus* Prakash from late Miocene sediments of the Karit Formation belonging to ITSZ. The anatomical details of the fossil wood, such as small to medium-sized vessels occluded with tyloses, scanty paratracheal to diffuse-in-aggregate axial parenchyma, 1–3 seriate homo to heterocellular rays, bordered intervessel pits with lenticular apertures and simple perforations, suggest its close affinity with *Diospyros* Linnaeus of the family Ebenaceae. Further anatomical details suggest a close resemblance with extant *D. ehretioides* Don and *D. macrophylla* Blume. The present fossil, along with previously known fossil records of *Lagerstroemia* (Lythraceae) and palms, indicate that the Trans-Himalaya was warm and humid during the late Miocene, quite different from the modern cool and dry climate in the study area.

Keywords: *Diospyros*; Ebenaceae; Ladakh; monsoon

1. Introduction

The collision and subsequent subduction of the northern margin of the Indian plate beneath the southern margin of the Eurasian plate led to the closure of Neotethys Sea and cessation of marine sedimentation (Henderson et al., 2010), and formation of high topography in south Asia (Fig. 1). The clastic and carbonate sedimentary rocks of the Indus-Tsangpo Suture Zone (ITSZ) between the Indian and Eurasian plates are often referred to the Indus Basin sedimentary rocks (IBSR), Indus Molasse, the Indus Formation, or the Kargil Formation (Shah et al., 1976; Frank et al., 1977; Gansser, 1977; Thakur, 1981; Searle et al., 1990; Clift et al., 2001; Wu et al., 2007; Henderson et al., 2010) (Fig. 2). The IBSR contains pre- and post-collision rocks and is important not only for understanding the uplift and erosional history of Himalaya, but also for constraining the timing of India-Eurasia collision (Henderson et al., 2010). The biota recovered from these IBSR successions are significant for understanding the paleoclimate and paleobiogeography of this region (Mehrotra et al., 2005; Patnaik, 2016).

Plant fossils are good indicators of past climate (Kershaw and Nix, 1988; Mosbrugger and Utescher, 1997; Greenwood et al., 2003, 2005; Fletcher et al., 2014;

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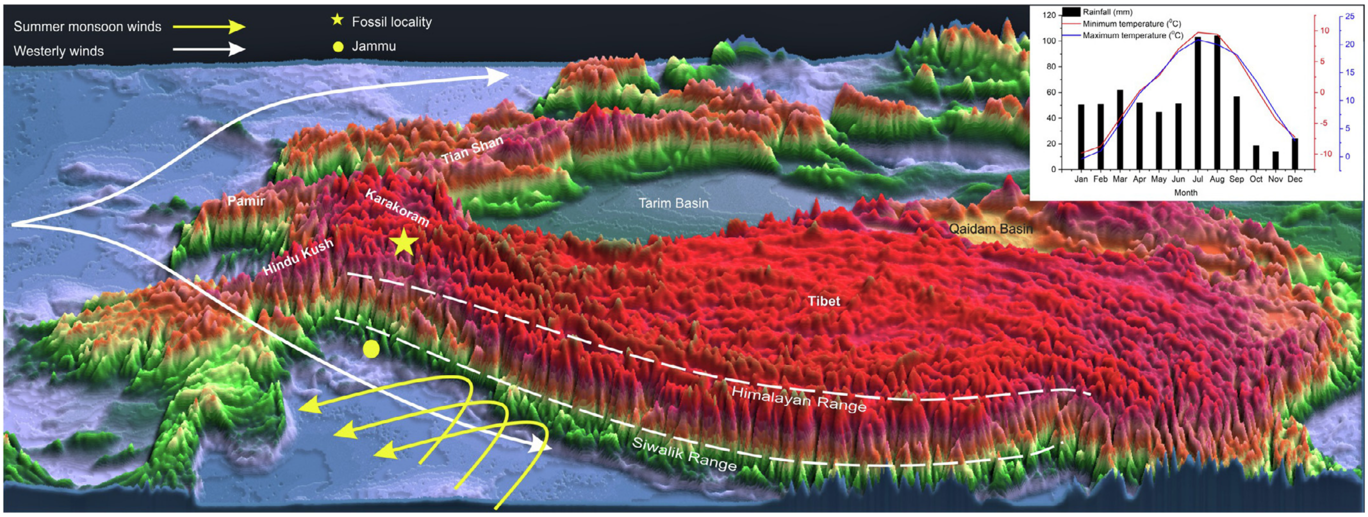


Fig. 1. Physiographic map of south Asia showing the fossil locality (yellow asterisk), Jammu (solid yellow circle), westerly and summer monsoon winds. The insert shows the modern rainfall and temperature pattern of the fossil locality.

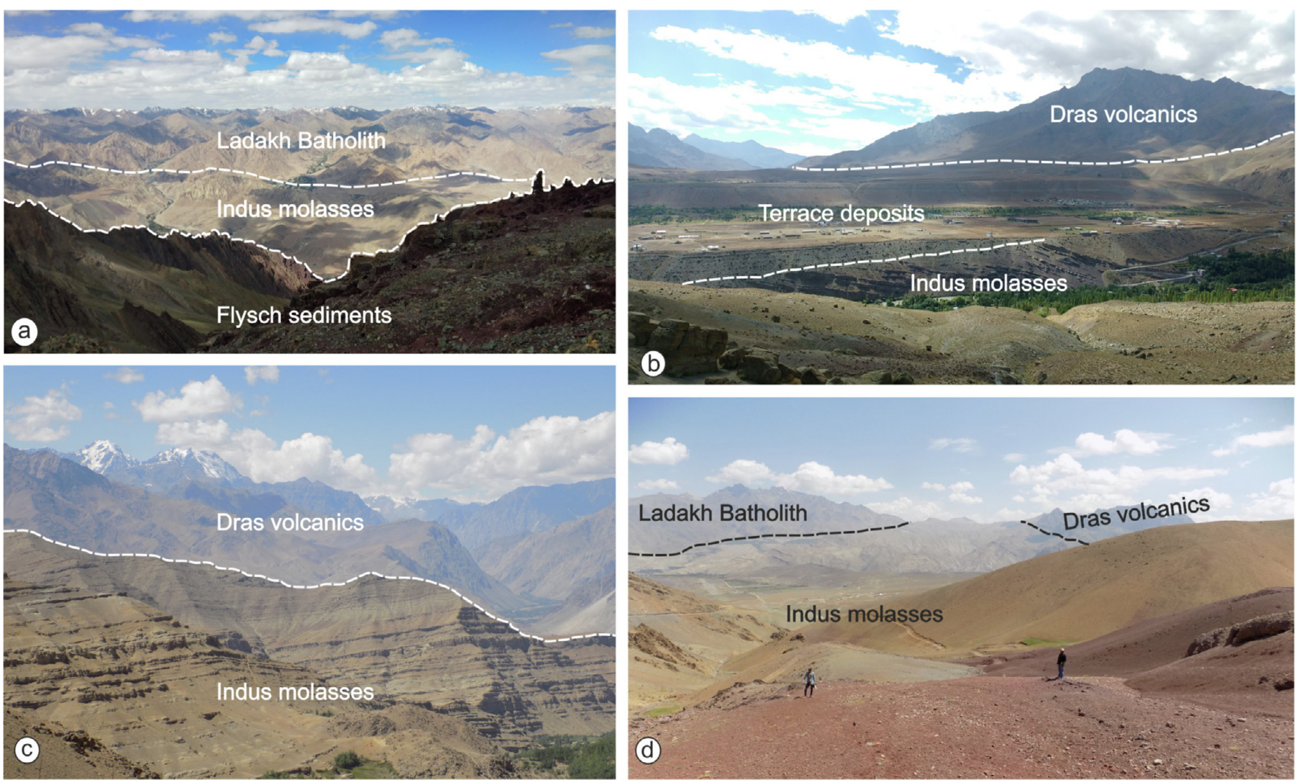


Fig. 2. Landscape photographs of the Indus-Tsango suture zone in the study area. (a) Field photograph showing demarcation of Flysch sediments, Indus molasse and the Ladakh Batholith. (b) Photograph showing demarcation of the Indus molasse, Terrace deposits and Dras volcanics. (c) Photograph showing demarcation between the Indus molasse and Dras volcanics. (d) Photograph showing demarcation of the Indus molasse, Ladakh Batholith and Dras volcanics.

Spicer et al., 2021). It has also been assumed that the climatic tolerances of most plants have remained more or less unchanged throughout the Neogene (MacGinitie, 1941; Hickey, 1977; Chaloner and Creber, 1990; Mosbrugger, 1999) and thus the nearest living relative (NLR) approach can be used for understanding Neogene climate (Mehrotra et al., 2011; Tiwari et al., 2012; Srivastava et al., 2016, 2017, 2018a, 2018b, 2018c). However, Neogene floristic records from the IBSR are rare and include only a few palms and fossil wood of *Lagerstroemia* and *Prunus* (Guleria et al., 1983; Lakhanpal et al., 1984; Mehrotra et al., 2014; Srivastava et al., 2018a).

In the present communication, we report for the first time well-preserved fossil wood ascribed to *Diospyros* from late Miocene sediments of the IBSR. Based on this fossil record, as well as previously reported taxa, we characterise the late Miocene climate of the Trans-Himalayan region in the western Himalaya.

2. Geology and age constraints of the study area

In the IBSR, Paleocene–Eocene marine flysch is succeeded by fluvial molasse deposits. Representing the youngest sedimentary succession of the Indus-Tsangpo Suture Zone (ITSZ), the Indus Group is exposed both in western and eastern Ladakh. The Indus molasse sedimentary succession is important due to its post-collision depositional characteristics that provide evidence of uplift and subsequent basin formation (Srivastava et al., 2018a). These sediments dominantly comprise a terrigenous clastic succession. The Indus Group sediments are structurally bounded to the south by the Indus Flysch, and the ophiolitic melange, while the northern margin of the Group onlaps the Ladakh Granitoid Complex.

The Indus molasse is exposed ubiquitously from Kargil to Hanle in Ladakh, India (Srikantia and Razdan, 1985) and continues into Tibet where it is known as the Xigaze Group (Tapponnier et al., 1981). Srikantia and Razdan (1985) divided the Indus molasse into the Skinding, Kuksho, Muklishun, and Karit formations in ascending order. However, the others have subdivided it into the Kargil, Tharumsa, and Pashkyum formations (Bhandari et al., 1977); the Nurla Formation, Choksti Conglomerate, Hemis Conglomerate, and Nimu Formation (Sinclair and Jeffey, 2001); and the Choksti, Lower Nimu, and Upper Nimu formations (Henderson et al., 2010) in ascending order.

The uppermost formation of the Indus molasse, i.e., the Karit/Pashkyum/Nimu/Upper Nimu, has been traced from Kargil to Nyoma. The Karit Formation is further divided into two, namely the Nurla and Hagnus members. The Nurla Member comprises siltstone and sandstone, whereas the Hagnus Member is characterised by conglomerate, pebbly sandstone, medium to coarse grained sandstone and siltstone. The sandstone unit of the Hagnus Member has yielded palm leaf impressions and fossil woods (Srivastava et al., 2018a). One of the wood specimens, identified as *Lagerstroemia* of the Lythraceae, has been systematically described (Srivastava et al., 2018a). The present fossil wood was recovered from the Karit Formation, i.e., the uppermost part of the Indus Molasse (Fig. 3).

The age of the Karit Formation is based on biostratigraphy, lithostratigraphy and Ar^{40}–Ar^{39}dating. Dixit et al. (1971) and Savage et al. (1977) suggested an early Miocene age based on the presence of the biostratigraphically significant fossil *Hyoboops*. However, Mathur (1983) suggested a late Miocene–Pliocene age for the same horizon based on fossil bivalves (*Indonaia bonneaudi*, *I. Glyptica* and *I. mittalli*) and a gastropod (*Melanoides tuberculata*). Subsequently, Henderson et al. (2010), using Ar^{40}–Ar^{39}dating of detrital mica, dated the Upper Nimu, the deposition of which is regarded as having been contemporaneous with that of the Karit Formation, as 23.7 (±0.2)–6.11 (±2.3) Ma. Based on the stratigraphic superposition of the Hagnus Member of the Karit Formation on the top of the Indus Group and biostratigraphically significant bivalves and gastropods, Srivastava et al. (2018a) suggested a late Miocene age for the plant fossils recovered from the Hagnus Member (Fig. 3).

3. Material and methods

Several dicot wood specimens were collected from the Lumsoo-Sumdo section (34°31'39.7″N, 76°24'37″E; 3559 m a.s.l.), northeast of Sumdo village, Kargil district, Ladakh (Fig. 1). These petrified wood remains were recovered from sandstones belonging to the Hagnus Member of Karit Formation, considered to be late Miocene in age (Fig. 3a, b). One specimen is identified and systematically described here, while the remainder awaits further study.

Slides were prepared by the standard method of cutting, grinding and polishing using various grades of carborundum powder (Lacey, 1963). The thickness of the sections was kept at about 30 µm. The slides are kept in repository of the Birbal Sahni Institute of Palaeosciences, Lucknow. The recommendations of the IAWA list of microscopic features for hardwood identification (IAWA, 1989) were followed while describing the fossil. The photographs were taken using a Leica Microscope DM2000.

4. Systematic palaeontology

Order Ericales Berchtold and Presl
Family Ebenaceae Gürke
Genus *Ebenoxylon* Felix

Ebenoxylon siwalicus Prakash
(Fig. 4)

Figured specimen: Specimen no. BSIP41975.
Repository: Birbal Sahni Institute of Palaeosciences, Lucknow.
Description: Wood diffuse-porous (Fig. 4a). Growth rings absent. Vessel round to oval, solitary and in radial multiples of 2–4, tangential diameter range 50–185 µm, mean 126 µm, medium to large, 12–16 per mm^2, profusely tylosed (Fig. 4a, d); vessel elements with horizontal to oblique ends, range 107–218 µm in length, mean 162 µm; perforations simple; intervessel pits bordered, alternate, oval, medium, 7–9 µm in diameter with lenticular apertures (Fig. 4f). Axial parenchyma mostly apotracheal, paratracheal scanty; apotracheal parenchyma diffuse to diffuse-in-aggregate forming single-celled broken irregular lines (Fig. 4a, d); cells 36–125 µm in height and 17–27 µm in width. Rays 10–13 per mm, 1–3 (mostly 2) seriate (Fig. 4b, c), made up of procumbent cells with 1 to 3 rows of upright or square cells, 18–47 µm in width and 7–30 cells

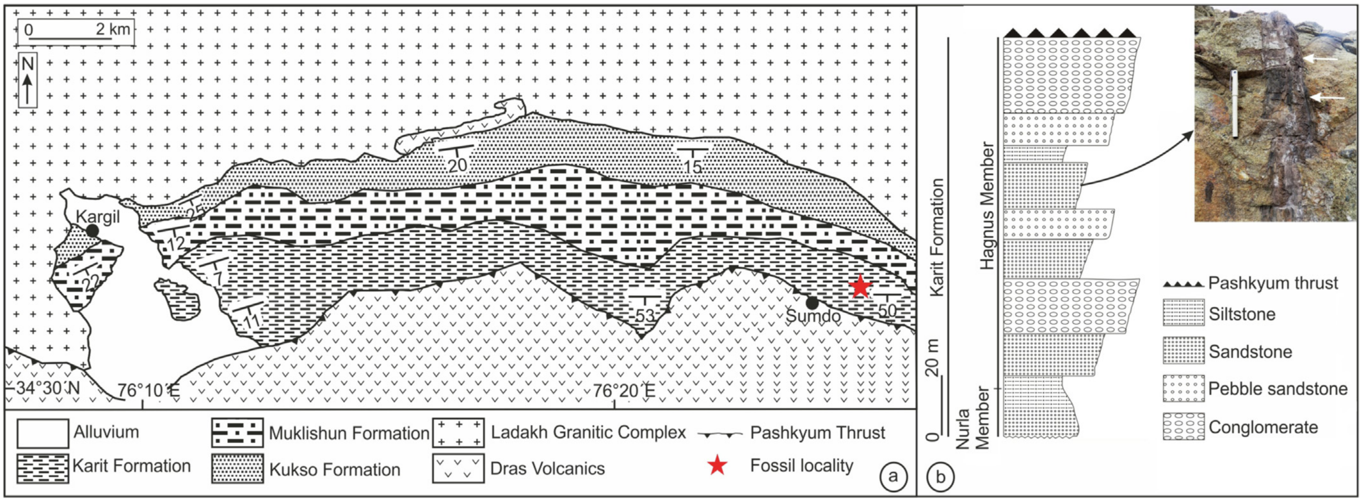


Fig. 3. Geology and stratigraphy of the studied area. (a) Geological map showing the Karit Formation containing the fossil wood in this study. (b) Lithologic sequence showing the sandstone horizon where the fossil wood (inset figure) was recovered.

or 210–587 µm in height; ray to ray fusion observed; ray tissue weakly heterogeneous, procumbent cells 10–19 µm in tangential height; upright or square cells 38–40 µm in tangential height (Fig. 4e). Fibres thick-walled and non-septate (Fig. 4c).

Remarks: The diagnostic features of the fossil wood, including diffuse porous wood, simple perforations, diffuse-in-aggregate axial parenchyma, thin rays and non-septate fibres, indicate its affinities with extant members of the families Apocynaceae, Ebenaceae, Rubiaceae and Sapotaceae (Pearson and Brown, 1932; Metcalfe and Chalk, 1950; Kribs, 1959; Ilic, 1991; InsideWood, 2004–onwards). The occurrence of broader rays and vasicentric tracheids in wood of Apocynaceae, Rubiaceae and Sapotaceae makes the present fossil wood distinct from these families. The presence of small to medium-sized vessels occluded with tyloses, scanty paratracheal to diffuse-in-aggregate axial parenchyma, 1–3 seriate homo- to heterocellular rays, bordered intervessel pits with lenticular apertures and simple perforations make the fossil closer to *Diospyros* of the family Ebenaceae. For detailed comparison with our fossil, we not only examined thin sections of the modern wood species of *Diospyros* available at the Birbal Sahni Institute of Palaeosciences, Lucknow, but also consulted published descriptions and photographs (Pearson and Brown, 1932; Metcalfe and Chalk, 1950; Kribs, 1959; Ilic, 1991; InsideWood, 2004–onwards). The fossil resembles the extant *Diospyros ehretioides* and *D. macrophylla* in almost all features, although profusely tylosed vessels are fewer in the modern wood. Thin sections of *Diospyros ehretioides* held at the Birbal Sahni Institute of Palaeosciences do not contain bordered pits in fibres, although the InsideWood website mentions their presence in fibres. Moreover, intervessel pits are slightly smaller in *D. macrophylla* than those in our fossil wood.

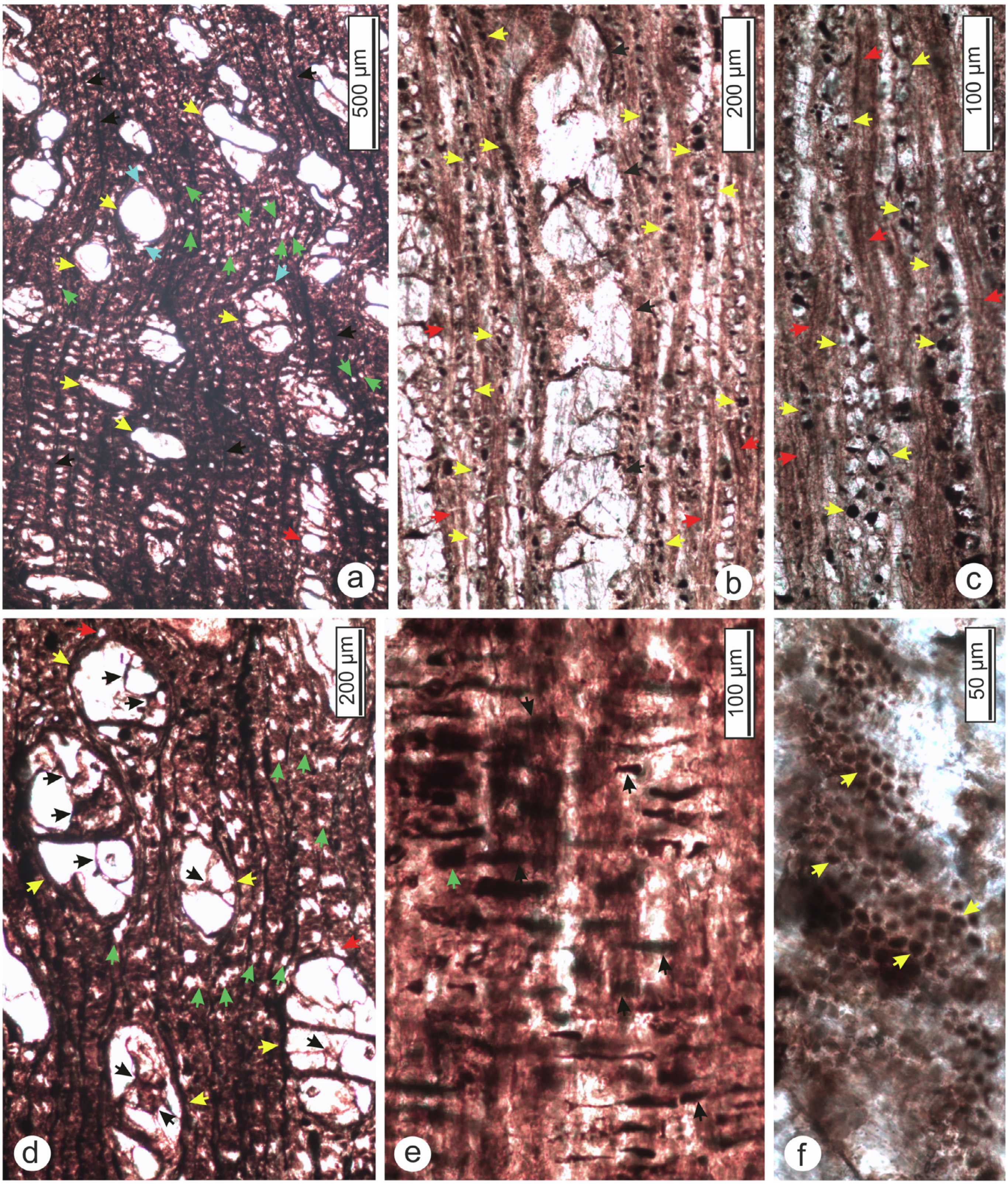
Diospyros is a large genus of over 732 species of evergreen and deciduous trees and shrubs widely distributed in tropical and temperate regions of the world (POWO, 2019). *Diospyros ehretioides*, the modern analogue of the fossil, is a species native to Southeast Asia, while *D. macrophylla* is found in Sumatra, Java, Borneo and Philippines (Fig. 5a, b).

In view of its close resemblance with the wood of *Diospyros*, the fossil has been assigned to the organ genus *Ebenoxylon* Felix, 1882, instituted to include fossil woods resembling *Diospyros*. Many species of *Ebenoxylon* described from various parts of India (Ghosh and Kazmi, 1958; Awasthi, 1970, 1984; Prakash and Tripathi, 1970; Prakash, 1978, 1981; Awasthi and Ahuja, 1982; Trivedi and Srivastava, 1982; Prasad, 1988, 1993; Antal et al., 1996; Mukherjee and Prasad, 2013; Awasthi et al., 2018) and elsewhere have been listed in Table S1. The present fossil was compared with all of them, but found to be closest to *Ebenoxylon siwalicus* Prakash. Since most fossil species of *Ebenoxylon* have been created on minor intraspecific variations, we refer our fossil to *Ebenoxylon siwalicus* instead of creating a new species.

Locality: Sumdo village, Kargil district, Ladakh, India.
Stratigraphic horizon: Karit Formation.
Age: Late Miocene.

5. Discussion

The collision between the Indian and Asian plates resulted in the rise of the Himalaya since Eocene (Ding et al., 2017). However, the rate of uplift increased during Neogene and the Greater Himalaya attained its modern elevation within the last 15 Ma (Garzione et al., 2000; Rowley et al., 2001; Saylor et al., 2009; Ding et al., 2017). The progressive uplift of the Himalaya during the Neogene resulted in the formation of the Himalayan Foreland Basin (HFB), also known as Siwalik basin, along the southern margin of the Himalaya (Fig. 1). Paleofloristic data recovered from the HFB (Siwalik basin) indicates that the uplift of the Himalaya had important implications in regard to changes in vegetation and the intensification of the south Asia monsoon (SAM) (Srivastava et al., 2018c; Bhatia et al., 2021). Climate modelling studies suggest that the Himalaya acts as a barrier between warm moist air in the south and cold dry air in the north (Boos and Kuang, 2010, 2013; Acosta and Huber, 2020). Plant fossils



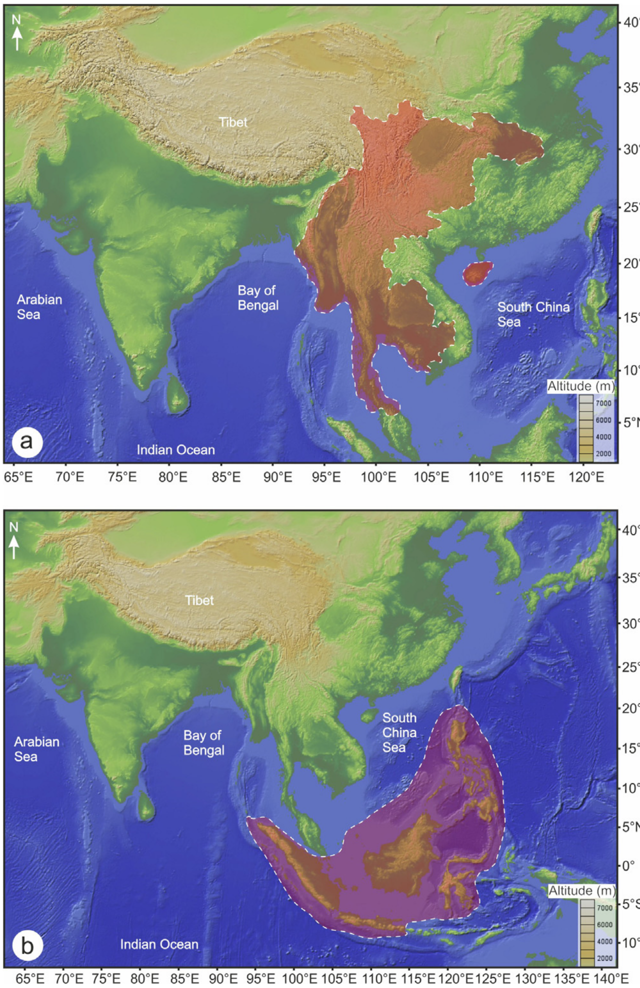


Fig. 5. Modern distribution of *Diospyros* Linnaeus shown by dotted lines. (a) Physiographic map showing the distribution of *Diospyros ehretioides* Don. (b) Physiographic map showing the distribution of *Diospyros macrophylla* Blume.

have been rarely reported from Himalayan hinterland Neogene sedimentary basins such as Trans-Himalayan region (Guleria et al., 1983; Lakhanpal et al., 1984; Paul et al., 2007; Srivastava et al., 2018a). Guleria et al. (1983) reported fossil wood of *Prunus* (Rosaceae) from the Kargil Formation of Ladakh. Subsequently, Lakhanpal et al. (1984) reported a palm leaf *Trachycarpus ladakhensis* from the Liyan Formation of Ladakh. Paul et al. (2007) also recorded a well-preserved palm leaf from the Hemis Formation. Recently, Srivastava et al. (2018a) described a fossil wood of *Lagerstroemia* from the Karit Formation. The Karit, Liyan and Hemis formations are considered as time equivalents, as they have been deposited as lithopackages in different parts of the Indus basin (Wangdus and Ramalingam, 1980–1981; Shanker et al., 1982; Lakhanpal et al., 1984; Paul et al., 2007).

The modern analogues of the fossil wood reported here from the Karit Formation, including *Diospyros ehretioides*, *D. macrophylla* and *Lagerstroemia parviflora*, along with several palms (unpublished), indicate that the climate was warm and humid during the deposition of the sediments. The presence of palms indicates that the CMMT (cold month mean temperature) was not less than 5°C and humid in the study area (Dransfield et al., 2008; Reichgelt et al., 2018). Furthermore, the complete absence of distinct ring porosity in the fossil wood, *Ebenoxylon siwalicus* Prakash, and previously described *Lagerstroemioxylon deomaliensis* Lakhanpal, Prakash and Awasthi (Srivastava et al., 2018a) from the same horizon, indicates a lack of seasonality in temperature and water availability. The floristic assemblage of Karit Formation indicates a warm and humid Trans-Himalaya, particularly in the study area, during late Miocene. However, the modern climate of the study area contrasts strongly with that of the late Miocene. Today, the area receives an annual average precipitation of only ~600–650 mm of which winter (December–February/DJF) and pre-monsoon (March–May/MAM) seasons jointly contribute ~44.9% of the total and the summer monsoon (June–September/JJAS) contributes ~49%.

More fossils are required from different parts of the Trans-Himalayan region to better understand the late Miocene climate. Similarly, exploration of more plant fossils from the Neogene sediments of Ladakh would help in understanding the influence of monsoonal climate in this topographically high region of south Asia.

6. Conclusions

We describe a late Miocene fossil wood specimen of *Ebenoxylon siwalicus* Prakash from the Karit Formation belonging to IBSR. The anatomical details of the fossil wood reveal its close affinity with *Diospyros* belonging to the family Ebenaceae. The fossil resembles most closely extant *D. ehretioides* and *D. macrophylla*. The modern ana-

Fig. 4. *Ebenoxylon siwalicus* Prakash. (a) Cross section of the fossil wood showing the distribution of vessels-both solitary (yellow arrows) and in radial multiples of 2–4 (red arrow), apotracheal (light green arrows) and paratracheal (turquoise arrows) axial parenchyma, and rays (black arrows) (BSIP museum no. 3a-c 41975). (b) Tangential longitudinal section (TLS) showing 1–3 seriate (mostly biseriate) rays (yellow arrows), vessel elements (black arrows) and fibres (red arrows) (BSIP museum no. 2a-b 41975). (c) TLS magnified showing 1–3 seriate rays (yellow arrows) and thick-walled fibres (red arrows) (BSIP museum no. 2a-b 41975). (d) Enlarged cross section showing vessels (yellow arrows) plugged with tyloses (black arrows), diffuse to diffuse-in-aggregate apotracheal parenchyma (light green arrows) and scanty paratracheal parenchyma (red arrows) (BSIP museum no. 3a-c 41975). (e) Radial longitudinal section of the fossil wood showing weakly heterogenous ray tissue made up of mostly procumbent cells (black arrows), and rarely upright/square cells (light green arrow) (BSIP museum no. 1a-b 41975). (f) Enlarged TLS showing the alternate intervessel bordered pits (yellow arrows) (BSIP museum no. 2a-b 41975).

logues of the fossil are today distributed in the Indo-China region and Southeast Asia, but not in the area of the fossil locality. The previous fossil record of *Lagerstroemia* from the same horizon, and the wood we describe here, along with several palm fossils (unpublished), indicate that the area was well vegetated and humid during late Miocene, in contrast to the modern climate of the area which is cold and dry. The most plausible reason for this change is the continued uplift of the Himalaya after the late Miocene.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palwor.2021.10.003.

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