

Rare Paleobotanical and Associated Paleontological Specimens from Madhya Pradesh: Stratigraphic Context, Paleoecology, and Biogeographic Implications: A Comprehensive Review

Sanjay Verma

Assistant Professor, Department of Botany

PMCOE Govt. Model Science College, Rewa, Madhya Pradesh

E-mail: he.sanjayverma@mp.gov.in

Abstract - Madhya Pradesh holds one of the most geologically continuous records of plant life on the Indian subcontinent. The strata spanning the Proterozoic Vindhyan Supergroup, the Gondwana sequences, and the Deccan Intertrappean beds preserve a fossil flora of rare scientific depth. This review examines the stratigraphic distribution and morphological character of key paleobotanical assemblages within these units, using botanical, xylotomical, and isotopic evidence to reconstruct the paleoenvironmental conditions under which they formed.

The analysis follows the fossil record from Early Mesoproterozoic cyanobacterial mats and simple acritarchs through the dominant *Glossopteris* coal swamps of the Permian, the gymnosperm woodlands of the Jurassic, and finally to the angiosperm diversification documented in the Deccan Intertrappean localities. Each transition reflects a distinct combination of climatic, tectonic, and ecological pressures. Triple oxygen isotope data from silicified Deccan wood indicate mean annual precipitation between 1,760 and 1,860 mm during the latest Cretaceous, arguing for a hyper-humid tropical environment rather than the semi-arid conditions suggested by earlier sedimentological models. The palaeobiogeographic record of these assemblages is assessed against three competing dispersal frameworks: vicariance, stepping-stone dispersal, and the Out-of-India hypothesis. The review concludes that the geobotanical archive of Madhya Pradesh constitutes a primary reference for understanding how tectonic isolation, Deccan volcanism, and the Cretaceous-Paleogene boundary event collectively shaped the tropical floristic heritage of the modern northern hemisphere.

Key Words: *Paleobotany, Vindhyan Supergroup, Gondwana flora, Deccan Intertrappean, acritarchs, Glossopteris, Pentoxylales, Out-of-India hypothesis, paleoecology, Madhya Pradesh*

1. THE GEBOTANICAL ARCHIVE OF CENTRAL INDIA

The sedimentary record of Madhya Pradesh spans an unusually broad segment of geological time. From unmetamorphosed Proterozoic carbonates in the Son Valley to the Deccan flood basalt sequences that bracket the Cretaceous-Paleogene boundary, the state preserves a near-continuous succession of environments that captured plant life at each major evolutionary transition. Few regions on the Indian subcontinent offer this stratigraphic breadth in such compact geographic proximity (Misra et al., 2009).

Three factors account for this exceptional preservation. First, the prolonged structural stability of the central Indian craton resisted deformation that elsewhere buried or obliterated fossil-bearing strata. Second, the formation of large intracratonic rift basins during the Paleozoic and Mesozoic created low-energy depositional environments where organic material accumulated and lithified with minimal disturbance (Torsvik & Cocks, 2013). Third, episodic interruptions of Deccan Trap volcanism produced isolated lacustrine basins that preserved plant material at ecological near-snapshots (Hooper et al., 2010).

Paleobotanical specimens from these units serve purposes that extend well beyond taxonomy. Organic-walled microfossils from the Vindhyan Supergroup constrain the timing of early eukaryote diversification. Silicified megaflores from the Gondwana sequences track the migration of the Indian plate across latitudinal climate gradients. Permineralized fruits and woods from the Intertrappean localities provide quantitative paleoclimatic proxies for the interval immediately before and after the mass extinction event at 66 Ma (Prasad et al., 2005; Schulte et al., 2010). Taken together, these assemblages generate an empirical record of how plant communities

responded to four major drivers over approximately 1.6 billion years: atmospheric change, tectonic movement, volcanism, and biological competition.

2. PROTEROZOIC MICROFLORAS OF THE VINDHYAN SUPERGROUP

The Vindhyan Supergroup, widely exposed in the Son Valley of eastern Madhya Pradesh, is the oldest sedimentary unit in the region to yield body fossils of biological significance. For several decades the precise age of this sequence was contested, with some researchers placing elements within the Cambrian. Isotopic dating combined with systematic biostratigraphic analysis of organic-walled microfossils has since constrained the depositional window to the Early Mesoproterozoic through Terminal Proterozoic, removing the sequence from those earlier attributions (Bengtson et al., 2009; Kumar & Sharma, 2012).

2.1 Early Mesoproterozoic Cyanobacterial Assemblages

The Semri Group, the basal division of the Vindhyan Supergroup, contains some of the oldest biologically interpretable material from central India. The Kajrahat Limestone formation preserves evidence of shallow marine carbonate platforms colonised by mat-forming cyanobacteria. The dominant taxa recorded from this unit include the filamentous forms *Polythrichoides*, *Karamia*, *Arctacellularia*, and *Siphonophycus* (Sharma et al., 1992). These filamentous organisms co-occur with simple *sphaeromorph acritarchs*, principally *Leiosphaeridia*, which represent the resting stages of unicellular planktonic algae (Strother et al., 2011).

The morphological conservatism of these cyanobacterial taxa across the Semri succession reflects the evolutionary stability that characterises organisms occupying stable, low-competition niches in early marine ecosystems. Their role in carbon fixation and the progressive oxygenation of shallow marine waters has broader significance for understanding the geochemical conditions of Early Mesoproterozoic oceans (Prasad et al., 2005; Knoll, 2003).

2.2 The Emergence of Eukaryotic Complexity

The Deonar Formation and overlying Kheinjua Subgroup record a biological transition of considerable significance. Where the Semri Group is dominated by simple prokaryotic forms, these younger beds yield

morphologically complex acanthomorph acritarchs, including *Tappania* spp. and the *polygonomorph Octoedryxium* (Bengtson et al., 2009). *Tappania* is particularly important because its structural organisation, with elongated processes and branched projections, requires a dynamic cytoskeleton of the kind found only in eukaryotic cells. Its presence in Deonar strata places eukaryote diversification firmly in the Mesoproterozoic rather than the Neoproterozoic, a point that carries weight in current debates about the pace of early animal evolution (Knoll et al., 2006).

2.3 Neoproterozoic Microfossils and the Ediacaran Transition

The upper Vindhyan sequences record the consequences of global climatic disruption during the Cryogenian. A major turnover in phytoplankton assemblages replaced Mesoproterozoic taxa with a Neoproterozoic flora dominated by *Trachysphaeridium laufeldi* and *Bavlinella faveolata* (Kumar & Sharma, 2012). The terminal Bhandar Group yields the spirally coiled cyanobacterium *Obruchevella*, a recognised Ediacaran biozone marker with an age range of 650 to 544 Ma (Corsetti & Hagadorn, 2000). Its occurrence in Madhya Pradesh provides a stratigraphic anchor for correlating the uppermost Vindhyan succession with global Ediacaran reference sections.

3. THE GONDWANA SUPERGROUP: PALEOZOIC AND MESOZOIC FLORAS

Fault-bounded depressions across Madhya Pradesh accumulated between 6 and 7 kilometres of fluvial and lacustrine sediments during the interval from the Upper Carboniferous to the Lower Cretaceous. Collectively designated the Gondwana Supergroup, these deposits track the vegetational history of the Indian plate from its position within high southern latitudes through its northward drift toward the equator (Chandra & Surange, 1979; Chatterjee & Scotese, 1999).

3.1 The Talchir Formation and Pioneer Flora

The Talchir Formation marks the retreat of Permian-Carboniferous glaciation from the Indian plate. The plant communities that colonised the resulting outwash plains were sparse and stress-tolerant. Dominant taxa include the seed fern *Gangamopteris* and the cordaitalean *Noeggerathiopsis*, both regarded as evolutionary precursors to the later and more diverse Glossopteris flora

(Maheshwari, 1992; Pant, 1996). Palynological sampling of these strata shows a consistent dominance of radial monosaccate pollen, whose aerodynamic construction facilitated wind dispersal across the open, unstabilised periglacial landscape (Rajanikanth et al., 2009).

3.2 The *Glossopteris* Flora and Peat-Forming Swamps

As the Indian plate drifted toward warmer latitudes during the Late Permian, open periglacial terrain gave way to dense, coal-forming forests dominated by *Glossopteris* (McLoughlin, 2001). The ecological success of this genus across Gondwana was tied partly to its root anatomy. Root casts preserved as *Vertebraria indica* reveal radially arranged chambers separated by aerenchyma tissue. This anatomy permitted oxygen delivery to the root tip through waterlogged peat, an essential adaptation for survival in chronically anoxic bog substrates (Chandra & Surange, 1979; Cleal & Thomas, 2005). The resulting swamp forests generated extensive peat deposits that now constitute the primary coal seams of the Barakar Formation, which remain economically productive across the Satpura coalfields of Madhya Pradesh.

3.3 Triassic Aridity and the *Dicroidium* Flora

The humid coal swamps of the Late Permian did not survive the end-Permian mass extinction event, which eliminated more than 80 per cent of marine species and severely restructured terrestrial vegetation globally (Retallack, 2013). Within the Indian basins, this transition is recorded by an abrupt shift from carbonaceous mudstones to red-bed fluvial facies, reflecting a move from humid to semi-arid conditions. The *Glossopteris* flora disappeared, replaced by the *Dicroidium* flora characteristic of Early to Middle Triassic recovery assemblages (Maheshwari, 1992). *Dicroidium* and associated taxa such as *Thinnfeldia* developed thickened, heavily cuticularised fronds suited to reducing water loss under conditions of high evaporative stress.

3.4 Jurassic and Early Cretaceous Gymnosperm Woodlands

The Upper Gondwana sequences record a return to warmer, more humid conditions during the Jurassic. The gymnosperm megaflores preserved in these beds is taxonomically diverse. Coniferous genera including *Araucarites* and *Brachyphyllum* indicate the development of a closed-canopy forest with moisture availability sufficient to sustain large arborescent growth (Bose et al.,

1985; Wheeler & Falcon-Lang, 2009). This gymnosperm woodland represents the vegetation context within which the first angiosperms had to compete for light and space during the subsequent Cretaceous period.

3.5 The *Pentoxylales*: An Isolated Gymnosperm Lineage

Among the most taxonomically unusual elements of the Upper Gondwana flora are members of the extinct gymnosperm order *Pentoxylales*. The type genus, *Pentoxylon sahnii*, described by Sahnii (1948), displays a vascular architecture consisting of five to six separate vascular strands arranged in a ring within the stem cross-section. This polystelic condition is not replicated in any other known gymnosperm lineage. The reproductive organs associated with *Pentoxylon*, the pollen-bearing *Sahnia* and the seed-bearing *Carnoconites*, show anatomical features with partial affinities to both cycads and Bennettitales without belonging clearly to either group (Bose et al., 1985). The *Pentoxylales* appear to represent a gymnosperm lineage that evolved in geographic isolation during the Mesozoic, achieving morphological specialization that left no direct modern descendants.

4. LATE CRETACEOUS PALEOENVIRONMENTS: BAGH BEDS AND LAMETA FORMATION

4.1 The *Bagh Beds* and Marine Incursion

The *Bagh Beds* of western Madhya Pradesh record a transgressive marine episode during which shallow seas extended inland from the retreating Tethys Ocean. The key biostratigraphic markers for this transgression are benthic inoceramid bivalves, particularly *Inoceramus concentricus*, which appear in the upper strata and confirm open marine salinity conditions during the Turonian Stage (Tandon et al., 1995). The *Bagh Beds* sit in stratigraphic contact with the underlying terrestrial Gondwana sediments and the overlying terrestrial Lameta Formation, making them an important marker horizon for sea-level reconstruction across the Cretaceous interior of the Indian plate (Chatterjee & Scotese, 1999).

4.2 The *Lameta Formation*: Terrestrial Archive

The *Lameta Formation*, best exposed in the Jabalpur region, provides a high-resolution record of the terrestrial environment immediately before the onset of Deccan volcanism. The formation is characterised by its

prominent Mottled Nodular Beds, which consist of vertically stacked pedogenic calcretes. Micromorphological and stable isotope analyses of these carbonates indicate precipitation through intense evaporation under a seasonal, semi-arid climate (Mohabey, 2001). This interpretation is consistent with the dinosaur egg assemblages recovered from the Lameta at multiple localities across Madhya Pradesh. The nesting behaviour inferred from clutch arrangements requires open, drying ground rather than waterlogged substrate, a nesting context that accords with the semi-arid paleosol reconstruction (Tandon et al., 1995; Srivastava & Mehrotra, 2013).

5. THE K-Pg BOUNDARY AND DECCAN INTERTRAPPEAN FLORAS

The Cretaceous-Paleogene boundary at approximately 66 Ma represents the most significant biotic crisis of the Cenozoic era. The mass extinction associated with the Chicxulub impactor eliminated approximately 76 per cent of all species globally, including all non-avian dinosaurs (Schulte et al., 2010). In Madhya Pradesh, this interval coincides with the main phase of Deccan Trap volcanism. Episodic pauses in lava extrusion allowed lacustrine and marsh environments to develop between successive flows, generating the Deccan Intertrappean Beds. Localities such as Mohgaon Kalan have yielded some of the most detailed permineralized plant assemblages known from any K-Pg boundary section globally (Prakash, 1960; Samant & Mohabey, 2009). These specimens preserve cellular anatomy at sufficient resolution to permit comparison with modern plant families.

5.1 Angiosperm Diversification: Capsular Fruit Anatomy

The Intertrappean beds document an angiosperm flora that is already highly derived by the time of deposition. The petrified capsular fruit *Sahnioacarpus* illustrates the morphological complexity achieved before the K-Pg boundary (Manchester et al., 2018). Its septicial dehiscence mechanism, in which the fruit splits along the septa separating adjacent seed chambers, aligns with dehiscence strategies found in several modern dicotyledonous families. The preservation of internal seed anatomy within permineralized specimens from Mohgaon Kalan confirms that this represents a reproductively functional structure rather than a body part preserved in post-mortem transport. Comparable angiosperm fruiting complexity has been documented from other K-Pg

boundary sections across the Tethyan belt (Friis et al., 2011).

5.2 Coryphoid Palm Radiation

Monocots, and coryphoid palms specifically, achieved substantial ecological presence before the K-Pg boundary. Palm foliage assigned to *Sabalites* from the Intertrappean beds shows the large, costapalmate leaf architecture characteristic of modern fan palms (Bande & Prakash, 1982). The size and complexity of these leaf specimens indicate palms that had achieved canopy-level stature and were not marginal components of the vegetation. This is ecologically significant because it places palms as structural dominants in the latest Cretaceous vegetation of central India rather than as recently arrived colonists still establishing themselves (Karanth, 2006).

5.3 Paleoclimatic Reconstruction: Xylotomy and Isotopic Evidence

Two independent lines of evidence converge on the same paleoclimatic conclusion for the Deccan Intertrappean interval. First, xylotomical analysis of silicified wood specimens from the Intertrappean beds shows a consistent absence of distinct growth rings. In living trees, growth rings form in response to seasonal interruptions of cambial activity caused by drought or temperature drop. Their absence in Deccan woods indicates continuous, aseasonal climate with no dry or cool season sufficient to arrest cambial activity, a pattern documented in modern equatorial forest timbers (Wheeler & Falcon-Lang, 2009). Second, triple oxygen isotope analysis of silicified wood, using the relationship between $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ values, provides a quantitative estimate of mean annual precipitation. Ghosh et al. (2020) report values corresponding to between 1,760 and 1,860 mm per year. This figure places the Deccan Intertrappean environment within the range of modern equatorial tropical rainforests, well above the threshold for closed-canopy forest structure. The combination of growth ring absence and high mean annual precipitation values argues against the semi-arid model previously proposed for this period and instead supports a hyper-humid paleoclimate sustained by the atmospheric injection of water vapour and carbon dioxide during the active volcanic phases of the Deccan event (Hooper et al., 2010).

6. PALEOBIOGEOGRAPHY AND THE TECTONIC MIGRATION OF THE INDIAN PLATE

Between the breakup of Gondwana during the Jurassic and the final collision of the Indian plate with Eurasia in the Eocene, India spent approximately 100 million years as an isolated landmass traversing the Tethys Ocean (Chatterjee & Scotese, 1999; Torsvik & Cocks, 2013). The biological consequences of this isolation are visible in the paleobotanical record, though they are more nuanced than simple models of complete evolutionary isolation would predict (Karanth, 2006).

6.1 Gondwanan Legacy and Vicariance

Several floral and faunal lineages preserved in the Cretaceous and Paleogene sediments of Madhya Pradesh retain clear Gondwanan ancestry. The vertebrate record reinforces this picture. Abelisaurid theropod remains from the Lameta Formation belong to a dinosaur lineage distributed across South America, Africa, Madagascar, and India, a pattern most parsimoniously explained by vicariance from a shared Gondwanan ancestor rather than by transoceanic dispersal (Mohabey, 2001). The plant record offers parallel evidence: several gymnosperm families present in the Gondwana sequences of Madhya Pradesh have their closest Cretaceous relatives in South America and Antarctica rather than in Laurasian floras of the same age (McLoughlin, 2001; Pant, 1996).

6.2 The Out-of-India Hypothesis and Dispersal Models

The diversification of angiosperms and coryphoid palms documented in the Deccan Intertrappean beds raises a different biogeographic question. If the Indian plate was geographically isolated during this radiation, the diversification occurred independently of Laurasian lineages. When the plate ultimately docked with Eurasia, it did not deliver impoverished relict flora. It delivered a suite of already highly derived tropical lineages that then spread into the Asian tropics and substantially altered the floristic composition of the region (Samant & Mohabey, 2009; Karanth, 2006).

The mechanism by which biological exchange may have occurred before final docking remains under active debate. The formation of volcanic island arcs along the converging plate margins during the Late Cretaceous and Paleocene could have provided dispersal corridors for plants with wind-dispersed seeds or floating propagules. Manchester et al. (2018) have argued that the fruit morphology of several Intertrappean angiosperm genera is

consistent with water or wind dispersal across relatively short open-water distances. A strict vicariance model cannot account for all elements of the Intertrappean flora, and a hybrid explanation involving both vicariance and limited stepping-stone dispersal represents the most defensible current position (Friis et al., 2011; Torsvik & Cocks, 2013).

7. SUMMARY TABLE OF KEY FOSSIL ASSEMBLAGES

Table 1 summarises the principal paleobotanical assemblages examined in this review, organised by stratigraphic unit, geological age, representative taxa, fossil preservation type, and paleoecological interpretation.

Table 1: Key Fossil Assemblages from the Paleobotanical Record of Madhya Pradesh

Stratigraphic Unit	Age	Representative Taxa	Fossil Type	Paleoecological Signal
Kajrahat Limestone (Semri Gp.)	Early Mesoproterozoic	<i>Siphonophycus</i> , <i>Leiosphaeridia</i>	Microfossil / Acritarch	Marine carbonate platform
Deonar Fm. (Kheinjua Sbgp.)	Late Mesoproterozoic	<i>Tappania</i> spp., <i>Octoedryxium</i>	Acanthomorph Acritarch	Eukaryote diversification
Bhandar Group (upper Vindhyan)	Neoproterozoic (~650 Ma)	<i>Obruchevella</i> , <i>Bavlinella</i>	Cyanobacterium	Ediacaran transition
Talchir Formation	Late Carboniferous	<i>Gangamopteris</i> , <i>Noeggerathiopsis</i>	Megafossil leaf	Periglacial outwash flora
Barakar Formation	Early Permian	<i>Glossopteris indica</i> , <i>Vertebraria</i>	Megafossil / Root cast	Coal swamp, peat bog
Panchet Formation	Early Triassic	<i>Dicroidium</i> , <i>Thinnfeldia</i>	Megafossil leaf	Post-extinction recovery
Rajmahal / Upper Gondwana	Jurassic to Early Cretaceous	<i>Pentoxylon sahnii</i> , <i>Araucarites</i>	Permineralized stem	Gymnosperm woodland
Lameta Formation	Late Cretaceous (Maastrichtian)	<i>Pedogenic calcrites</i> , <i>sauropod</i> eggs	Ichnofossil / Egg	Semi-arid floodplain
Deccan Intertrappean Beds	Late Cretaceous to Paleogene	<i>Sahnioarpon</i> , <i>Sabalites</i>	Petrified fruit / Leaf	Tropical rainforest

Sources: Compiled from Sharma et al. (1992), Kumar & Sharma (2012), Chandra & Surange (1979), Maheshwari (1992), Bose et al. (1985), Sahnii (1948), Tandon et al. (1995), Mohabey (2001), Bande & Prakash (1982), Manchester et al. (2018), Ghosh et al. (2020), Prasad et al. (2005).

8. SYNTHESIS AND CONCLUSIONS

The paleobotanical record of Madhya Pradesh spans approximately 1.6 billion years of biological history. Its depth and stratigraphic continuity make it one of the most informative regional fossil plant archives in South Asia. This review has traced that record through four analytically distinct phases, each carrying its own scientific implications.

The Vindhyan microfloras establish the Meso-Neoproterozoic age of the basin's depositional history and provide direct morphological evidence for eukaryote diversification before 1,000 Ma (Knoll et al., 2006; Bengtson et al., 2009). The absence of metamorphic overprinting in these sediments is a taphonomic advantage that the broader community has not yet fully exploited. Further systematic sampling of the upper Vindhyan sections in eastern Madhya Pradesh is likely to yield additional acritarch taxa relevant to current debates about the pace of Proterozoic biological innovation.

The Gondwana flora sequence records the most complete terrestrial vegetational succession in the region. The transition from Glossopteris coal swamps through Triassic recovery assemblages to Jurassic gymnosperm woodlands captures the combined effects of the end-Permian mass extinction, subsequent climatic instability, and the northward latitudinal drift of the Indian plate across roughly 30 degrees of latitude (Retallack, 2013; McLoughlin, 2001). The Pentoxylales remain the most scientifically distinctive element of this record: a gymnosperm order with no living relatives, no clear phylogenetic placement within the seed plant tree of life, and an anatomical organisation pointing to a sustained period of independent Mesozoic evolution.

The Deccan Intertrappean data resolve an older controversy in Indian paleoclimatology. The semi-arid interpretation of the latest Cretaceous environment of central India, derived primarily from sedimentological evidence in the Lameta Formation, does not survive comparison with silicified wood anatomy and triple oxygen isotopes. The mean annual precipitation estimates of Ghosh et al. (2020) are internally consistent and corroborated by independent botanical proxies. Central India during the latest Cretaceous was wet. The Deccan eruptions maintained a hyper-humid tropical environment through their active phases rather than inducing desiccation.

Biogeographically, the record supports neither total biotic isolation nor unrestricted exchange between the Indian plate and Eurasia before docking. Gondwanan vicariance explains the deep ancestry of several gymnosperm and vertebrate lineages (Chatterjee & Scotese, 1999). The Out-of-India hypothesis remains the most coherent framework for explaining the subsequent spread of derived tropical plant lineages into the Asian tropics following final plate collision (Karanth, 2006; Samant & Mohabey, 2009; Friis et al., 2011).

Continued systematic fieldwork in the Vindhyan outcrop belt, combined with isotopic and tomographic analysis of Intertrappean permineralized material, will refine each of

these conclusions. The geobotanical archive of this region is still being read.

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