Permian macro- and miofloral diversity, palynodating and palaeoclimate implications deduced from the coal-bearing sequences of Singrauli coalfield, Son–Mahanadi Basin, central India

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The coal-bearing sequences of Barakar and Raniganj formations exposed in Bina and Jhingurdah open-cast collieries, respectively, are analysed for their macro- and miofloral content. The sediment successions primarily comprise of sandstones, shales, claystones and coal seams. In addition to the diverse glossopterid assemblage, four palynoassemblage zones, namely Zones I and II in Bina Colliery and Zones III and IV in Jhingurdah Colliery, have also been recorded in the present study. The megafossil assemblage from the Barakar strata of Bina Colliery comprises of three genera, namely *Gangamopteris*, *Glossopteris* and cf. *Noeggerathiopsis*. Palynoassemblage-I is characterised by the dominance of non-striate bisaccate pollen genus *Scheuringipollenites* and subdominance of striate bisaccate *Faunipollenites* and infers these strata to be of Early Permian (Artinskian) age (Lower Barakar Formation). The palynoassemblage has also yielded a large number of naked fossil spore tetrads, which is the first record of spore tetrads from any Artinskian strata in the world and has a significant bearing on the climatic conditions. The palynoassemblage-II is characterised with the dominance of *Faunipollenites* over *Scheuringipollenites* and is indicative of Kungurian age (Upper Barakar Formation). The megafossil assemblage from the Raniganj Formation of Jhingurdah Colliery comprises of five genera with 26 species representing four orders, viz., Equisetales, Cordaitales, Cycadales and Glossopteridales. The order Glossopteridales is highly diversified with 23 taxa and the genus *Glossopteris*, with 22 species, dominates the flora. The mioflora of this colliery is represented by two distinct palynoassemblages. The palynoassemblage-III is correlatable with the palynoflora of Early Permian (Artinskian) Lower Barakar Formation. The assemblage suggests the continuity of older biozones into the younger ones. The palynoassemblage-IV equates the beds with composition V: *Striatopodocarpites*–*Faunipollenites*–*Gondisporites* assemblage zone of Tiwari and Tripathi (1992) of Late Permian (Lopingian) Raniganj Formation in Damodar Basin. The FAD's of *Alisporites*, *Klausipollenites*, *Falcisporites*, *Arcuatipollenites pellucidus* and *Playfordiaspora cancellosa* palynotaxa in this assemblage enhance the end Permian level of the Jhingurdah Top seam, as these elements are the key species to mark the transition of Permian into the Lower Triassic.

1. Introduction

The Singrauli coalfield lies in the north-western part of Son–Mahanadi Master Basin and spreads

in the states of Uttar Pradesh and Madhya Pradesh. The coalfield has 10 opencast collieries of which coal-bearing sequences of nine collieries (Dudhichua, Jayant, Kakri, Bina, Krishnashilla,

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Amlohri, Khadia, Block B and Nigahi) belong to the Barakar Formation, whereas Jhingurdah Colliery is in Raniganj Formation. All the nine collieries of Barakar Formation have three coal seams, i.e., the lowermost Turra seam, middle Purewa bottom and the uppermost Purewa top coal seam. Jhingurdah Colliery situated in the north-eastern part of Singrauli coalfield has two coal seams, Jhingurdah Top and Jhingurdah Bottom. It has the thickest coal seam (Jhingurdah) in India (130 m). The Talchir Formation is mostly exposed in the northern and eastern parts of the coalfield.

In comparison to the other coalfields of the Son–Mahanadi Basin, the Singrauli coalfield has not received much attention as far as the macrofloral studies are concerned. However, the coalfield has been well investigated for its palynological (bore-core data) and petrological aspects in the past by many workers (Trivedi 1950; Pareek 1969, 1970; Tiwari 1969, 1971; Sinha 1969, 1972; Bharadwaj and Sinha 1969a, b; Tiwari and Srivatsava 1984; Tiwari and Ram-Awatar 1989; Mishra and Singh 1990; Singh and Mishra 1991; Vijaya *et al.* 2012; Singh and Singh 2014; Saxena *et al.* 2016a). Barring the initial investigations by Lele (1966) and Lele *et al.* (1968) who reported the glossopterid mega plant fossils in the Talchir and Barakar sediments exposed in the eastern part of the coalfield, and the comprehensive morphotaxonomic studies carried out on Raniganj Formation of the Jhingurdah Colliery (Singh and Saxena 2015) and on the Barakar Formation of Bina Colliery (Saxena *et al.* 2016b), no other megafloal studies have been attempted so far.

The aim of the present communication is to ascertain the palynostratigraphic status and age of the studied strata and to envisage the significant changes in floral composition, and associated climatic conditions responsible for the floristic evolution through the Permian time in Singrauli coalfield based on the macro- and microfloal investigations. To address this issue, the macrofloral and palynological observations derived from the Barakar and Raniganj sediments of Bina and Jhingurdah collieries have been taken into consideration. Detailed systematic descriptions of the megafloal assemblages of both the collieries have already been published elsewhere (Singh and Saxena 2015; Saxena *et al.* 2016b; Singh *et al.* 2016). Herein, the dataset of these recently analysed megafloal assemblages, studies based on the macrofloral remains of the Talchir and Barakar outcrops of Singrauli coalfield (Lele 1966; Lele *et al.* 1968) and the present palynological investigations on the different coal seams of both these collieries are used to decipher the gradual and gradational changes in mega and microfloal composition and development of *Glossopteris* flora throughout the Permian in this coalfield.

2. Geology of the area

The Singrauli coalfield (figure 1) lies at the northern-most boundary of the Son–Mahanadi Master Basin that stretches from the east coast to the centre of Peninsular India. This coalfield embodies the last deposits of the Gondwana sedimentation. Therefore, no sediments of Gondwana period occur beyond this coalfield area in the northern part of Peninsular India. It lies between latitudes 23°47'–24°12' and longitudes 81°48'–82°52' and is located in the drainage area of Son and Rihand rivers. The total geographical area of this coalfield is around 2200 km²; approximately 80 km² comes in the Sonbhadra District of Uttar Pradesh State, and the rest fall in Singrauli District of Madhya Pradesh State.

The coalfield is structurally divided into two tectono-sedimentary sub-basins: (i) Moher sub-basin on the north-eastern side and (ii) the Singrauli main sub-basin to the west. There is no clear cut demarcation between these two sub-basins because all the Lower Gondwana formations are exposed uninterruptedly in these sub-basins. The sediments of Permian representing Talchir, Barakar, Barren Measures and Raniganj formations are extensively exposed in the Moher sub-basin, whereas the Triassic sediments belonging to Panchet (Pali) and Mahadeva (Parsora) formations are mainly confined to the Singrauli main sub-basin. The only difference between both the sub-basins lies in the number of coal reserves found in them. All the ten working opencast mines of Singrauli coalfield, *viz.*, Dudhichua, Jayant, Kakri, Bina, Krishnashilla, Amlohri, Khadia, Block B, Nigahi and Jhingurdah come under Moher sub-basin. Barring Jhingurdah, the rest of the collieries are in Barakar Formation and have three coal seams, i.e., the lowermost Turra seam, middle Purewa bottom and the uppermost Purewa top. All these seams reserve good quality of coal. The Barakar sediments mainly consist of medium to coarse grained, light grey, feldspathic sandstones, shales, clays and coal seams. Jhingurdah Colliery is in Raniganj Formation and has the thickest coal seam (134 m) in India. It also has the deepest basal area among all other collieries of this coalfield. The Raniganj sediments consist of medium to coarse-grained sandstone, grey shale, carbonaceous shale, claystone and coal seams.

Based on the surface and subsurface data acquired so far, the generalised stratigraphic succession developed in the Singrauli coalfield is given in table 1.

3. Material and methods

The material described and discussed in this paper comprises megafossils and palynological samples

Figure 1. Location map of Singrauli coalfield showing Bina and Jhingurdah collieries (after Raja Rao 1983).

collected from the Barakar and Raniganj formations of Bina and Jhingurdah collieries, respectively. The plant fossil assemblage of Bina Colliery is recorded from its Purewa Bottom and Turra coal seams. The Purewa bottom seam has yielded good fossil assemblage, whereas from the Turra seam, only rootlets are procured. For the palynological analyses, three samples (BC/TS-0, BC/TS-1 and BC/TS-2) were collected from a section of the Turra Seam and another set of three samples (BC/PB-1, BC/PB-2 and BC/PB-3) were collected from the Purewa Bottom seam. The fossiliferous

horizons and respective lithologies are shown in figures 2 and 3.

Well-preserved plant macrofossils were procured from the grey shale and mudstone units of a coal-bearing sequence, *viz.*, Jhingurdah Top seam belonging to Raniganj Formation (Lopingian) from the Jhingurdah Colliery and includes impressions of leaves, equisetalean axes and *in-situ* preserved roots. The photograph of the section and corresponding lithology containing *Glossopterid* remains, stems and *in-situ* preserved *Vertebraria* roots along with palynological samples are shown

Table 1. General stratigraphic succession of Singrauli coalfield (after Vijaya *et al.* 2012).

Age	Formation/group	Thickness	General lithology
Recent			Alluvium
Cretaceous	Basic intrusive		Dolerite dykes and sills
Late Triassic	Parsora (Mahadeva)	500 m+	Medium-to-coarse grained ferruginous quartzose sandstone
Early Triassic	Pali (Panchet)	700 m+	Greenish yellow to reddish yellow, medium-to-coarse grained sandstone with variegated siltstone and clay
Late Permian	Raniganj	215–400 m	Fine-to-medium grained dirty to buff coloured subarkosic to feldspathic wacke with alternation of thin lamination of grey and carbonaceous shale along with impersistent coal seams
Middle Permian	Barren Measures	110–300 m	Dark brown to brownish yellow to greenish grey, medium-to-coarse grained flaggy sandstone with thin grey clay bands in between
Early Permian	Barakar	325–550 m	Dirty white fine-to-coarse grained sub-arkosic to arkosic sandstone along with siltstone, shale, carbonaceous shale and coal seams
Early Permian	Talchir	75–230 m	Dark greenish grey to grey shale, fine grained sandstone diamictite, siltstone pebbly sandstone and boulder bed
<i>Unconformity</i>			
Precambrian	Mahakoshal		Granite, gneiss, quartzite, phyllite, schist and pegmatite

in figure 4. Three palynological samples (JC/JB-1, JC/JB-2, JC/JB-3) were collected from the Jhingurdah Bottom coal seam and two palynological samples (JC/JT-1, JC/JT-2) were collected from Jhingurdah Top coal seam (figure 4).

For the megafloral analysis, around 215 specimens were studied and identified up to genus and species level. Their morphotaxonomy and detailed description have already been dealt (Singh and Saxena 2015; Saxena *et al.* 2016b; Singh *et al.* 2016), wherein the combined data set of both the collieries is used to assess the change in floral composition through the Permian.

For the palynological analyses, sediments are processed using standard maceration technique. Each sample, weighing 50 g of sediments, was crushed and treated with 40% hydrofluoric acid for 3–4 days to remove silica material, and then followed by treatment with nitric acid for 5–6 days for digestion of humic matter. Thereafter, they were treated with 5% potassium hydroxide to release all the humus. The macerals were mounted on the slides using polyvinyl alcohol and Canada balsam. Five slides from each sample were

prepared and pollen spores were observed under the transmitted light microscope (Olympus-BX-61); the photographs were taken using Digital Olympus camera (DP-20).

Based on the quantitative and qualitative representation of the palynomorphs, different palynoassemblages are identified which are correlated with the standard assemblage zones established by Tiwari and Tripathi (1992) and further the age bracket assigned by the GSSP sections to the Permian Period as correlated and discussed by Mukhopadhyay *et al.* (2010) for the interbasinal correlation of different formations in Indian Gondwana basins. A Late Palaeozoic portion of the stratigraphic correlation chart and respective ages based on Mukhopadhyay *et al.* (2010) is given in table 2.

4. Megafloral observations

4.1 Talchir megafloral assemblage

The floral composition recovered from the Talchir Formation (Early Permian = Asselian–Sakamarian)

Figure 2. (a) Photograph showing measured section of a part of Turra Seam, Bina Colliery, Singrauli coalfield. (b) Lithocolumn depicting different lithounits of a part of Turra Seam. * indicates the position of palynological samples.

Figure 3. (a) Photograph of the section of a part of Purewa Bottom coal seam of Bina Colliery depicting megafossil and palynological horizons. (b) Litholog of the section yielding megafossil and palynological assemblages.

Figure 4. (a) Panoramic view of Jhingurdah Top coal seam of Jhingurdah Colliery, ‘star’ indicates the position of figure 4(b). (b) Photograph of the section yielding megafossil and palynological assemblages. (c) Generalised litholog of the section of Jhingurdah Top coal seam. Star indicates megafossil-bearing horizons and triangle mark denotes the position of palynological samples.

Table 2. Correlation of Late Palaeozoic Gondwana basins (after Mukhopadhyay et al. 2010).

Gondwana Sedimentary Basins →					Damodar-Koel	Rajmahal	Southern Mahanadi	Son	Satpura	Godavari
251 Ma	Time Slot III	Permian	Lopingian		Raniganj		Raniganj	Raniganj	Bijuri	Lr. Kamthi
260 Ma			Guadalupian		Barren Measures		Barren Measures	Barren Measures	Motur	Barren Measures
271 Ma	Time Slot II		Cisuralian	Kungurian	Up. Barakar	Up. Barakar	Up. Barakar	Up. Barakar	Up. Barakar	Up. Barakar
278 Ma				Artinskian	Lr. Barakar/ Karharbari	Lr. Barakar	Lr. Barakar	Lr. Barakar	Lr. Barakar	Lr. Barakar
290 Ma	Time Slot I	Sakmarian		Talchir	Talchir	Talchir	Talchir	Talchir	Talchir	
299 Ma 302 Ma		Asselian								
Carboniferous				Gzhelian

Non-deposition/Erosion

has revealed the occurrence of *Noeggerathiopsis*–*Gangamopteris* assemblage (Lele 1966; Lele et al. 1968). The flora is completely devoid of the genus *Glossopteris*. The taxon *Noeggerathiopsis hislopii* is the most abundant element followed by *Gangamopteris cyclopteroides*, *G. cf. major* and *Gangamopteris* sp. Besides, seeds of *Samaropsis* cf. *S. goraiensis* and stem casts were also reported in the Talchir assemblage (table 3).

4.2 Barakar megafloral assemblage

The megafossil assemblage recovered from the coal-bearing sequence of the Barakar Formation of Bina Colliery is mostly represented by leaves belonging to three genera, namely *Gangamopteris*, *Glossopteris* and cf. *Noeggerathiopsis*. Among these, the genus *Glossopteris* dominates with eight species namely, *Glossopteris browniana*, *Glossopteris* cf.

Table 3. A list of complete megafossil assemblages recovered from Talchir, Barakar and Raniganj formations of Singrauli coalfield.

Talchir Formation*	Barakar Formation	Raniganj Formation
<i>Gangamopteris cyclopteroides</i> Feistmantel (1876)	* <i>Gangamopteris</i> cf. <i>G. angustifolia</i> McCoy (1875)	<i>Paracalamites</i> sp. Zalessky
<i>G. cf. G. major</i> Feistmantel (1879)	* <i>G. cyclopteroides</i> Feistmantel (1876) * <i>G. cyclopteroides</i> var. <i>areolata</i>	<i>Euryphyllum</i> sp. Feistmantel (1879)
<i>Gangamopteris</i> sp. McCoy (1847)	Feistmantel (1879) <i>Gangamopteris</i> sp.	<i>Macrotaeniopteris</i> cf. <i>M. feddenii</i> Feistmantel (1876)
<i>Noeggerathiopsis hislopi</i> (Bunbury) Feistmantel (1879)	<i>Glossopteris browniana</i> Brongniart (1828) * <i>Glossopteris communis</i> Feistmantel (1876) <i>G. cf. G. cordatifolia</i> Feistmantel (1890)	<i>Glossopteris angustifolia</i> Brongniart (1828)
<i>Samaropsis</i> cf. <i>S. goraiensis</i> Surange and Lele (1957) Stem casts	* <i>G. indica</i> Schimper (1869) <i>G. gigas</i> Pant and Singh (1971) <i>G. leptoneura</i> Bunbury (1861) <i>G. nakkarea</i> Chandra and Surange (1979) <i>G. pantii</i> Chandra and Surange (1979) <i>G. recurva</i> Pant and Singh (1974) * <i>G. sp. cf. taeniopteroides</i> <i>G. tenuifolia</i> Pant and Gupta (1968) <i>Glossopteris</i> sp. cf. <i>Noeggerathiopsis</i> sp.	<i>G. arberi</i> Srivastava (1956) <i>G. barakarensis</i> Kulkarni (1971) <i>G. browniana</i> Brongniart (1828) <i>G. communis</i> Feistmantel (1879) <i>G. conspicua</i> Feistmantel (1881) <i>G. cf. G. cordatifolia</i> Feistmantel (1890) <i>G. gigas</i> Pant and Singh (1971) <i>G. giridihensis</i> Pant and Gupta (1971) <i>G. gondwanensis</i> Pant and Gupta (1971) <i>G. indica</i> Schimper (1869) <i>G. karharbariensis</i> Chandra and Surange (1979) <i>G. linearis</i> McCoy (1847) <i>G. mohudaensis</i> Chandra and Surange (1979) <i>G. nimishea</i> Chandra and Surange (1979) <i>G. oldhamii</i> Pant and Singh (1974) <i>G. stenoneura</i> Feistmantel (1881) <i>G. stricta</i> Bunbury (1861) <i>G. subtilis</i> Pant and Gupta (1971) <i>G. tenuifolia</i> Pant and Gupta (1968) <i>G. zeilleri</i> Pant and Gupta (1968) <i>Glossopteris</i> sp. Brongniart (1828) <i>Vertebraria indica</i> Royle (1839)
	* <i>Samaropsis</i> sp. Göppert (1864) * <i>Cordaicarpus</i> sp. Geinitz (1862)	
	*Coniferous shoot (? <i>Buriadia</i>) *Equisetalean stem *Notched leaf	
	Rooting structures Stem casts Stem axes (impression) Bifurcating/branching axes Seeds Scale leaf Fertile structures Ruptured/assorted meshes	Thin slender axes Stem axes Root branches

Note. * indicates contributions from Lele (1966).

G. cordatifolia, *G. gigas*, *G. leptoneura*, *G. nakkarea*, *G. pantii*, *G. recurva* and *G. tenuifolia*, whereas the remaining genera are represented by one species each (table 4, figure 5). Many ill-preserved impressions representing scale leaves, seeds, fertile structures, branching axes/roots and stem casts have also been found in this assemblage. In addition to Bina flora, Lele *et al.* (1968) had also reported the presence of *Gangamopteris* cf. *G. angustifolia*, *G. cyclopteroides*, *G. cyclopteroides* var. *areolata*, *Glossopteris communis*, *G. indica*, *G. sp. cf. G. taeniopteroides* and seeds of *Samaropsis* and *Cordaicarpus*. A coniferous shoot (?*Buriadia*) and few equisetalean axes were also reported in this assemblage (table 3).

A close examination of the entire Barakar assemblage reveals the dominance of *Glossopteris* over the genus *Gangamopteris*. Moreover, the leaves of *Glossopteris* are fairly medium to large in size (1.9–14.8 cm in length and 1.2–5.3 cm in width) and mostly are middle to broad mesh forms. The flora is devoid of the groups lycopodiales, filicales, sphenophyllales, cycadales and ginkgoales.

4.3 Raniganj megafloreal assemblage

Complete flora of Raniganj Formation, as recovered from the Jhingurdah Top seam of Jhingurdah Colliery, consists of five genera with 26 species representing four orders, *viz.*, Equisetales (*Paracalamites*),

Table 4. Relative percentages of various *Glossopteris* species recovered from Raniganj Formation of Jhingurdah Colliery (dominant: >10%; sub-dominant: 4–10%; rare: 2–4%; extremely rare: 0–2%).

Sl. no.	Name of <i>Glossopteris</i> species	Percentages
Dominant		
1	<i>G. sp.</i>	24.09
2	<i>G. tenuifolia</i>	14.45
Sub-dominant		
3	<i>G. nimishea</i>	8.43
4	<i>G. arberi</i>	7.22
5	<i>G. communis</i>	6.02
6	<i>G. stricta</i>	4.81
7	<i>G. browniana</i>	4.81
Rare		
8	<i>G. cf. G. cordatifolia</i>	3.61
9	<i>G. stenoneura</i>	3.61
10	<i>G. indica</i>	3.61
11	<i>G. barakarensis</i>	2.4
12	<i>G. giridihensis</i>	2.4
13	<i>G. zeilleri</i>	2.4
14	<i>G. linearis</i>	2.4
Extremely rare		
15	<i>G. karharbariensis</i>	1.2
16	<i>G. angustifolia</i>	1.2
17	<i>G. oldhamii</i>	1.2
18	<i>G. mohudaensis</i>	1.2
19	<i>G. gondwanensis</i>	1.2
20	<i>G. subtilis</i>	1.2
21	<i>G. conspicua</i>	1.2
22	<i>G. gigas</i>	1.2
Total		99.86

Cordaitales (*Euryphyllum*), Cycadales (*Macrotaeniopteris*) and Glossopteridales (*Glossopteris* and *Vertebraria*) (table 3). The order Glossopteridales is highly diversified with 23 taxa and the genus *Glossopteris* with 22 species dominates the flora, whereas the remaining genera have one species each (table 4). Barring the genus *Vertebraria*, the other genera namely *Paracalamites*, *Euryphyllum* and *Macrotaeniopteris* have rare occurrence (figure 6).

Most of the *Glossopteris* species found in Raniganj Formation are either narrow mesh forms or medium mesh forms and are relatively smaller in size. *Glossopteris tenuifolia* is the most dominant species (14.45%) of this genus followed by *G. nimishea* (8.43%) and *G. arberi* (7.22%). The group Glossopteridales is a dominantly preserved group. The assemblage of Jhingurdah Colliery is mostly dominated by medium mesh forms of the genus *Glossopteris*. In association with the leaf impressions, a large number of vertically preserved *Vertebraria* roots (65 specimens, accounting for 41.6%) are also found. The groups Lycopodiales, Filicales, Sphenophyllales, Ginkgoales and

Coniferales are completely missing in the Raniganj Formation of this coalfield.

5. Palynological observations

The yield of palynomorphs in the samples is rich. In addition to this, palynodebris such as cuticle, wood flinters, structured and unstructured organic materials and amorphous matter are also present. The preservation of palynomorphs is fair to good. Based on the qualitative and quantitative analyses of the spores and pollen taxa, four distinct palynoassemblages have been identified in the Barakar and the Raniganj formations (two in each formation) (table 5). The relative occurrences of the taxa vary from rare (less than 1%), common (1–5%), fair (5–10%) to abundant (11–25%) and to dominant (>25%) in an assemblage (figure 7, frequency chart). The details of each palynoassemblage are given below and the important palynotaxa are shown in figures 7 and 8.

5.1 Palynoassemblage I

Sample nos. BC/TS-0, BC/TS-1 and BC/TS-2 from Turra coal seam.

All the three samples have yielded very rich assemblage of the palynomorphs. An unusual occurrence of naked spore tetrads was recorded in the sample no. BC/TS-0. The palynological details are given below as the following:

Dominant: *Scheuringipollenites*

Sub-dominant: *Indotriradites* and *Parasaccites*

Other taxa: *Faunipollenites*, *Striatopodocarpites*, *Verticypollenites*, *Densipollenites*, *Weylandites circularis*, *Tiwariasporis simplex*, *Sahanites* sp., *Distriatites bilateris*

Trilete spore: *Microfoveolatispora foveolata*

Age marker taxa: *Indotriradites*, *Faunipollenites varius*, *Rhizomaspora indica*, *Arcuatipollenites ovatus* and *Callumispora* sp.

Palynodating: The assemblage is rich in having zonate trilete spores. The occurrence of pollen taxa *Scheuringipollenites*, *Parasaccites* and *Striatopodocarpites* and spore taxon *Callumispora* in abundance along with other species, viz., *Indotriradites*, *Microfoveolatispora*, *Rhizomaspora* and *Densipollenites* in this palynoassemblage is similar to that known from the lower part of the Barakar Formation in the Damodar Basin, in having abundance of *Scheuringipollenites*, *Parasaccites* and *Faunipollenites* along with the age marker species. Palynoassemblage-I can be correlated with *Scheuringipollenites barakarensis* Assemblage-I of Tiwari and Tripathi (1992). The recovered palynocomposition place these beds at the transition of Karharbari Formation and Lower Barakar Formation and date them as late Early Permian (Artinskian).

Figure 5. Relative percentages of various genera and *Glossopteris* species from Barakar Formation of Bina Colliery.

Figure 6. Relative percentage of various genera/groups collected from the Raniganj Formation of Jhingurdah Colliery.

In addition to these palynomorphs, an unusual dominance of spore tetrads is recorded in the sample no. BC/TS-0, which are assignable to the dispersed microspore genera *Indotriradites*, *Microbaculispora* and *Microfoveolatispora*. Tetrads form a sizeable chunk, about 17% of the total palynoassemblage consisting of 15 spore/pollen genera. This is the first record of tetrads from any Artinskian strata in the world. Their significance and role of being a possible indicator of the intense climatic regime (extreme cold) has been envisaged

and already established (Saxena *et al.* 2016a). Apart from the spores-pollen content, the predominance of cuticle and amorphous matter, plant tissues is also noted in this assemblage.

5.2 Palynoassemblage-II

Sample nos. BC/PB-1, BC/PB-2 and BC/PB-3 from Purewa Bottom coal seam

Dominant: *Faunipollenites*

Sub-dominant: *Scheuringipollenites*

Table 5. *Palynoassemblage zones derived from the Barakar and Raniganj formations, interpreted ages and important palynotaxa.*

Palynoassemblage zones	Composition	Assemblage zone identified	Formation	Age inferred on the basis of palyno-assemblages
Palyno-assemblage-IV	Dominance of <i>Striatopodocarpites</i> and subdominance of <i>Faunipollenites</i> along with <i>Scheuringipollenites</i> and non-striate bisaccate such as <i>Alisporites</i> , <i>Falcisporites</i> , etc. and stratigraphically age marker taxa are <i>Crescentipollenites</i> , <i>Arcuatipollenites</i> , <i>Klausipollenites</i> , <i>Playfordiaspora</i> , <i>Striasulcites</i> , <i>Hamiapollenites</i> and <i>Striamonosaccites</i> . <i>Triletes</i> are poor, represents <i>Foveolatispora</i> , <i>Calamisporea</i> .	<i>Gondisporites raniganjensis</i> (<i>Striatopodocarpites</i> – <i>Faunipollenites</i>)	Raniganj	Late Permian
Palyno-assemblage -III	Dominance of <i>Faunipollenites</i> followed by <i>Scheuringipollenites</i> and lesser number of <i>Striatopodocarpites</i>	<i>Scheuringipollenites barakarensis</i>	Raniganj	Early Permian
Palyno-assemblage-II	Dominance of <i>Scheuringipollenites</i> along with fair presence of <i>Laviegatospore</i> . Other taxa rare in presence are: <i>Faunipollenites</i> , <i>Striatopodocarpites</i> , <i>Rhizomaspora</i> , <i>Verticypollenites</i> , <i>Dicappipollenites</i> , <i>Parasaccities</i> , <i>Barakarites</i> , <i>Densipollenites</i> and <i>Foveolatispora</i>	<i>Scheuringipollenites barakarensis</i>	Barakar	Early Permian
Palyno-assemblage-I	Dominance of <i>Scheuringipollenites</i> and tetrad spores and sub-dominance of <i>Parasaccites</i> followed by <i>Rhizomaspora</i> , <i>Striatopodocarpites</i> , <i>Verticypollenites</i> , <i>Faunipollenites</i> <i>Indotriletes</i> , <i>Arcuatipollenites</i> with dark amorphous matter and woody flinters.	<i>Scheuringipollenites barakarensis</i>	Barakar	Early Permian

Other taxa: *Densipollenites*, *Barakarites*, *Parasaccites*, *Striatopodocarpites* and *Rhizomaspora*.

The recovery of spore pollen varies on an average from low to medium. Besides these palynomorphs, woody shreds, plant tissues and organic matter were abundant. Qualitative analysis of the palynoassemblage suggests an age younger than Lower Barakar in having characteristic palynomorphs namely, *Faunipollenites* and *Scheuringipollenites* in fair occurrence, followed by the presence of *Densipollenites* pollen. The other stratigraphically important pollen grains are *Barakarites*, *Parasaccites*, *Striatopodocarpites* and *Rhizomaspora*. The trilete spores are scarce and are represented by *Microfoveolatispora* and *Varietrilites*.

Palynodating: This assemblage compares well with the *Faunipollenites varius* Assemblage Zone of Tiwari and Tripathi (1992) and dates Purewa Bottom Seam as Upper Barakar (Kungurian) in age having the dominance of *Faunipollenites* over the *Scheuringipollenites*.

5.3 Palynoassemblage-III

Sample nos. JC/JB-1, JC/JB-2 and JC/JB-3 from Jhingurdah Bottom Coal Seam

In this coal seam, the sample nos. JC/JB-1 was found to be unproductive.

Dominant: *Scheuringipollenites*

Sub-dominant: *Faunipollenites*

Other taxa: *Striamonosaccites ovatus*, *Crescentipollenites*, *Hemiapollenites*, *Striatites*, *Verticypollenites*, *Corriasaccites*, *Barakarites*, *Dicappipollenites* and *Rhizomaspora*

Trilete: *Callumisporea*, *Microfoveolatispora*, *Laevigatospores*

Age marker taxa: *Scheuringipollenites barakarensis*, *Microbaculispora barakarensis*, *Horriditriletes curvibaculosus* and *Barakarites indica*.

Palynodating: Assemblage-III compares well with the *Scheuringipollenites barakarensis* Assemblage Zone of Tiwari and Tripathi (1992) in having the dominance of *Scheuringipollenites* and

Figure 7. Palynomorphs recovered from the Barakar Formation of Bina Colliery, Singrauli coalfield. 1. *Callumispora fungosa* Balme (1973); 2. *Microfoveolatispora* sp.; 3, 4. *Indotriradites korbaensis* Tiwari (1964); 5. *Indotriradites mamillatus* Bhardwaj and Tiwari (1977); 6. *Indotriradites* sp.; 7. *Indotriradites sparsus* Tiwari (1964); 8. *Parasaccites obscures* Tiwari (1965); 9. *Parasaccites korbaensis* Bhardwaj and Tiwari (1964); 10. *Densipollenites invisus* Bharadwaj and Salujha (1964); 11. *Densipollenites magnicarpus* Tiwari and Rana (1981); 12. *Striamonosaccites ovatus* Bharadwaj (1962); 13. *Distriamono-colpites ovalis* Bharadwaj and Salujha (1969); 14. *Playfordiaspora cancellosa*; 15. *Scheuringipollenites tentula* Tiwari (1973); 16. *Scheuringipollenites maximus* Tiwari (1973); 17. *Scheuringipollenites barakarensis* Tiwari (1973); 18. *varius* Bharadwaj (1962); 19. *Striatopodocarpites decorus* Bharadwaj (1964).

Figure 8. Palynomorphs recovered from the Raniganj Formation of Jhingurdah Colliery, Singrauli coalfield. 1. *Crescentipollenites fuscus* Bharadwaj, Tiwari and Kar (1974); 2. *Verticypollenites oblongus* Bharadwaj (1962); 3. *Rhizomaspota indica* Tiwari (1965); 4. *Rhizomaspota radiata* Wilson (1962); 5. *Distriatites bilateris* Bharadwaj (1962); 6. *Arcuatipollenites* sp.; 7. *Arcuatipollenites ovatus* Tiwari and Vijaya (1995); 8. *Arcuatipollenites pellucidus* Tiwari and Vijaya (1995); 9. *Klausipollenites staplainii* Jansonicus (1962); 10. *Alisporites*; 11. *Alisporites australis* de Jersey (1962); 12. *Alisporites ovalis* Kumar (1973); 13. *Satsangisaccites nidpurensis* Bharadwaj and Srivastava (1969); 14. *Alisporites splendens* (Leschick) Foster (1979); 15. *Falcisporites mulhallensis* Balme (1970); 16. *Dicappipollenites crassus* (Sinha) Tiwari and Vijaya (1995); 17. *Crustae-sporites globosus* Leschick (1956); 18. *Weylandites minutes* Bharadwaj and Srivastava (1969); 19. *Laevigatosporites plicatus* Kar (1968).

sub-dominance of *Faunipollenites* along with other age marker taxa. It is dated as late Early Permian (Artinskian) in age. Apart from spores-pollen, cuticle, amorphous matter and other plant tissues were also observed.

5.4 Palynoassemblage-IV

Sample nos. JC/JT-1 and JC/JT-2 from Jhingurdah Top Coal Seam

Dominant: *Striatopodocarpites*

Sub-dominant: *Faunipollenites*

Other taxa: *Scheuringipollenites*, *Alisporites*, *Falcisporites*, *Hamiapollenites*, *Striamonosaccites* and *Distriatites*. Triletes are poor, represented with *Microfoveolatispora* and *Callumispora*.

Age marker taxa: *Crescentipollenites*, *Arcuatipollenites*, *Klausipollenites*, *Playfordiaspora* and *Striasulcites*.

Palynodating: The Palynoassemblage IV is very similar to the known palynoflora recovered from lower part of the Raniganj Formation in Damodar Basin. Dominance of striate bisaccate taxon *Striatopodocarpites* and sub-dominance of *Faunipollenites* followed by *Distriatites*, *Striamonosaccites* palynomorphs equates these beds with Palynoassemblage Zone-V, viz., *Striatopodocarpites*–*Faunipollenites*–*Gondisporites* Assemblage Zone of Tiwari and Tripathi (1992), and dates them as Late Permian (Lopingian) in age. FAD's of *Alisporites*, *Klausipollenites*, *Falcisporites*, *Arcuatipollenites pellucidus* and *Playfordiaspora cancellosa* palynotaxa enhance the end Permian level, as these elements are the key species to mark the transition of Permian into the Lower Triassic.

6. Discussion

The macro- and microfossil studies of the Lower Gondwana sequences belonging to the Talchir, Barakar and Raniganj formations of Singrauli coalfield, have been carried out to assess the palynostratigraphic status and age of the studied strata; significant changes that had occurred in floral composition and in the associated climatic conditions responsible for the floristic variations through the Permian time in the Singrauli coalfield basin. The macroflora recovered from the Talchir (Early Permian) strata has revealed the occurrence of *Noeggerathiopsis*–*Gangamopteris* complex, which is completely devoid of the genus *Glossopteris*. The Barakar Formation is represented by diverse *Gangamopteris*–*Glossopteris* assemblage, whereas the flora of Raniganj Formation (Lopingian) is typically *Glossopteris* dominated flora that completely lack the genus *Gangamopteris*. The Talchir flora consists of the earliest representatives

of the *Glossopteris* flora, i.e., *Gangamopteris* and *Noeggerathiopsis*, which are considered to be the pioneer elements of the earliest Permian (Asselian) time.

In comparison to the prolific occurrence of the macrofloral remains in the Raniganj Formation, the presence of such remains is remarkably less in the Barakar Formation (table 3). However, the leaves of the Barakar assemblage are quite big in size and medium to broad mesh forms, as compared to relatively smaller and narrow-medium mesh leaves of the Raniganj Formation (Lele 1966; Saxena *et al.* 2016b). The richness, as well as the diversity, of the megaflora in Bina Colliery is comparatively very low, however, they have been observed quite high in the Barakar Formation of other coalfields namely, Talcher (Saxena *et al.* 2014), Ib-River (Singh *et al.* 2006) and Korba (Singh *et al.* 2011) of the Son–Mahanadi Basin. Further, none of the megafossils is preserved with cuticle, suggesting the complete oxidation of the carbon content of the preserved fossils at least in these facies. On the contrary, the species diversity of the genus *Glossopteris* is very high in the Raniganj floral assemblage as compared to its diversity in the Barakar assemblage. The *Glossopteris* plants were seemingly deciduous as is evidenced by the fact that a large number of its leaves are found preserved singly/individually in different layers of sediments of Jhingurdah Top seam. There are around 156 specimens of various taxa (table 3) in the present Raniganj assemblage; most of them are well preserved with minor distortion, indicating that deposition site of the vegetal matter was not very far from the original growing site and deposition took place in a low energy environment. Moreover, in addition to the leaves and equisetalean axes preserved as impressions, the Raniganj flora of this coalfield comprises very well preserved *in-situ* *Vertebraria* roots, which are not reported from the Barakar and Talchir formations of this coalfield.

Generally the climate during the deposition of Raniganj/Lower Kamthi Formation was warm and humid with intermittent rainfall that resulted in the development of dense forests of Glossopterid trees having medium-to-large sized leaves; and small herbs and shrubs belonging to Pteridophytes and other gymnosperms used to grow underneath these plants (Chandra and Chandra 1988; Chandra and Singh 1992; Goswami and Singh 2013). Such climatic conditions also favoured the production of diverse fructifications as evidenced by the occurrence of these in the sediments along with the sterile leaves (Maheshwari 1965; Chandra and Singh 1992). The occurrence of comparatively small-sized leaves of various species of *Glossopteris* and also the complete absence of fructifications in the Jhingurdah Top seam of this colliery advocates the

existence of warm and semi-arid conditions in this area that possibly did not allow these plants to blossom and produce fructifications and also restricted their ability to bear normal leaves.

The macrofloral assemblages recovered from all the three formations are completely devoid of the plant groups Lycopodiales, Sphenophyllales, Filicales and Ginkgoales suggesting that the Moher Sub-basin area might not be adequately cool and humid to facilitate the growth of these shade-loving, under-storied plants.

It is very difficult to date the sediments precisely on the mere basis of macroflora, however, the mioflora as well as the fauna always acted as a better proxy for determining the precise dates. We have correlated and dated the studied sections with the help of palynology. Four distinct palynoassemblages, namely I and II from Bina Colliery and III and IV from Jhingurdah Colliery have been recorded and interpreted to assess the biostratigraphic status of the studied strata (table 5). The entire strata including coal seams of Bina and Jhingurdah collieries have been broadly kept in the Barakar and Raniganj formations, respectively (Raja Rao 1983). However, the present palynological investigations carried out on the known coal seams in these collieries resulted in the confirmation of the sediments of Lower Barakar and Upper Barakar in Bina Colliery and of Lower Barakar and Raniganj Formation in Jhingurdah Colliery. The identified palynoassemblages have been strictly correlated with the known and established palynoassemblage zones of Tiwari and Tripathi (1987, 1992) based on the stratigraphical importance of the age marker taxa, and their relative occurrence along with other associated significant species.

The dominance of the taxon *Scheuringipollenites* followed by *Indotriradites* and *Parasaccites* in association with *Faunipollenites* and other taxa in Palynoassemblage-I from the Turra seam correlates these beds with Early Permian (Artinskian) Lower Barakar Formation. This palynoassemblage resembles very well with the *Scheuringipollenites barakarensis* Palynoassemblage Zone-V of Tiwari and Tripathi (1992) and also with the Palynocomposition III (A) of Tiwari and Tripathi (1987), which indicates the prevalence of a cool climate with high humidity during this period in Singrauli coalfield. The palynoassemblage-I is also comparable with the Lower Barakar palynoflora of the northern part of Singrauli coalfield (Vijaya *et al.* 2012), as well as other basins of India (Bharadwaj and Srivastava 1973; Srivastava 1973; Tiwari 1973; Bharadwaj *et al.* 1974; Tiwari *et al.* 1981; Srivastava and Jha 1992, 1996; Murthy *et al.* 2010; Vijaya *et al.* 2011).

Palynoassemblage-II, from the Purewa Bottom seam, with *Faunipollenites* as the dominant taxon, followed by *Scheuringipollenites*, *Densipollenites*, *Barakarites*, *Parasaccites*, *Striatopodocarpites* and *Rhizomaspora* seems to be quite similar to the *Faunipollenites varius* Palynoassemblage Zone-VI of Tiwari and Tripathi (1992) and also to the Palynocomposition III (B) of Tiwari and Tripathi (1987), which signifies the existence of moderately warm climate with high humidity. Based on the palynocomposition of this assemblage, the beds can be placed in late Early Permian (Kungurian) Upper Barakar Formation.

Palynoassemblage-III from the Jhingurdah Bottom Seam has dominance of taxon *Scheuringipollenites* followed by *Faunipollenites*, *Verticipollenites*, *Barakarites*, *Crescentipollenites*, *Corriasaccites*, *Laevigatosporites* and is comparable with the *Scheuringipollenites barakarensis* Assemblage Zone-V of Tiwari and Tripathi (1992) and can be assigned Early Permian (Artinskian) age (Lower Barakar). However, the miospore assemblage recovered from the bore-core of Jhingurdah seam (top and bottom) had a close affinity with the palynoassemblage of Upper Barakar Formation (Bharadwaj and Sinha 1969b). In a subsequent reappraisal, the mioflora of Jhingurdah seam was re-examined and found to be closely comparable with the known miofloras of Raniganj Formation (Tiwari and Srivastava 1984). In the present study, the palynoflora of Jhingurdah bottom seam shows affinities with the palynoflora of Lower Barakar, whereas the Palynoassemblage-IV from Jhingurdah Top seam is closely comparable with the mioflora of Raniganj Formation. Such ambiguity in the palynodating needs further thorough re-investigations to resolve this issue.

Palynoassemblage-IV from the Jhingurdah Top Seam is characterised by the dominance of striate bisaccate *Striatopodocarpites* and *Faunipollenites* in association with stratigraphically important taxa, namely *Alisporites*, *Arcuatipollenites*, *Playfordiaspora*, *Striasulcites*, *Klausipollenites* and *Densipollenites*. The Palynoassemblage-IV is compared with the *Striatopodocarpites-Faunipollenites-Gondisporites* Assemblage Zone of Tiwari and Tripathi (1992) in Damodar Basin, thus assigning a Late Permian (Lopingian) age. This assemblage is also comparable with the Assemblage-III of East Bokaro coalfield (Vijaya *et al.* 2012) and palynoassemblage-II of Sohagpur coalfield (Ram-Awatar *et al.* 2004). The presence of *Alisporites*, *Klausipollenites*, *Falcisporites*, *Arcuatipollenites* and *Playfordiaspora* palynotaxa along with other Late Permian palynomorphs in the Jhingurdah Top seam also place these beds at the transition of Late Permian and Lower Triassic.

7. Conclusions

- Earliest Permian (Asselian) Talchir Formation witnessed the lowest plant diversity in Moher sub-basin of Singrauli coalfield (total five taxa representing three genera, viz., *Gangamopteris*, *Noeggerathiopsis* and *Samaropsis*). The complete absence of the forms having a midrib, i.e., *Glossopteris* in this formation may be attributed to extreme cold conditions with very low humidity in Talchir time (Tiwari and Tripathi 1987) that probably restricted the development of such midrib possessing Glossopterids.
- The moderately warm climate with high humidity during the deposition of Barakar Formation (Tiwari and Tripathi 1987) has resulted in the development of diversified macrofloras including forms with well-defined midrib representing six genera (?*Buriadia*, *Gangamopteris*, *Glossopteris*, cf. *Noeggerathiopsis*, *Samaropsis* and *Cordaicarpus*) and 17 taxa.
- The flora further evolved and diversified in the Raniganj Formation as evidenced by the occurrence of five genera with 26 species in the Jhingurdah Top seam of Jhingurdah Colliery. The genus *Glossopteris* with 22 species tops the diversity scale, however, the relatively smaller size of leaves of various species of *Glossopteris* and also the complete absence of the fructifications in this seam advocates the preponderance of warm and semi-arid conditions in this area that possibly did not allow these plants to grow normally and produce fructifications.
- Identification of *Scheuringipollenites barakarensis* and *Faunipollenites varius* Palynoassemblage Zones in the Turra and Purewa Bottom seams of Bina Colliery, respectively, have led to the assignment of an Early Permian (Artinskian–Lower Barakar) age to Turra seam and late Early Permian (Kungurian–Upper Barakar) age to Purewa Bottom coal seam.
- The occurrence of *Scheuringipollenites barakarensis* Palynoassemblage Zone in the Jhingurdah Bottom coal seam of Jhingurdah Colliery is unbelievable as this seam otherwise belongs to Raniganj Formation, however, Jhingurdah Top seam certainly is of Late Permian (Lopingian) age because of the occurrence of *Striatopodocarpites*–*Faunipollenites*–*Gondisporites* Palynoassemblage Zone in it.
- The FAD's of *Alisporites*, *Klausipollenites*, *Falcisporites*, *Arcuatipollenites* and *Playfordiaspora* palynotaxa observed in the Jhingurdah Top seam enhance the end Permian level and also place these beds at the transition of Late Permian and Lower Triassic.

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