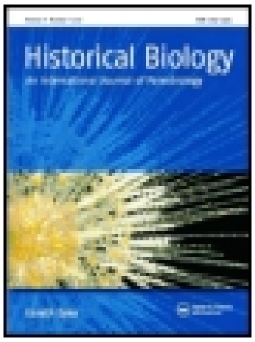

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ARTICLE

Late Pennsylvanian and Early Cisuralian palynofloras from the Rajmahal Basin, eastern India, and their chronological significance

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ABSTRACT

This work documents for the first time a palynological assemblage in the Rajmahal Basin, tentatively considered probable youngest Late Pennsylvanian assemblage, which was hitherto considered early Permian. The palynocomposition consists of 39 species (5 spores, 25 monosaccate, 5 bisaccate- 3 non striate and 2 striate grains, scarce *Navifusa* sp., scolecodont, algae and fungal hyphae). Two assemblages are described based on the first appearance of taxa, Assemblage I (608.90–599.00 m) dominated by monosaccates and absence of bisaccates and spores. Assemblage II (592.0–590.80 m) also dominated by monosaccates but with the inception of spores, bisaccates and marine palynomorphs. The Assemblage I is correlated to the oldest *Potonieisporites neglectus* Assemblage Zone of Tiwari and Tripathi based on their similarities and the absence of species recorded in the Assemblage II which is correlated to their overlying *Plicatipollenites gondwanensis* Assemblage Zone. Palynoassemblages similar to the Assemblage I, radiometrically constrained to the Late Pennsylvanian across Gondwana, along with the lack of diagnostic Permian pollen grains as well as marine *Eurydesma* fauna and terrestrial glossopterids, tentatively support an older age at least for the lower interval of the Talchir Formation. The latter fossils associated to Assemblage II confirm an early Permian age.

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Introduction

The Rajmahal Basin has drawn the attention of many workers as it is a classic area of tholeiite magmatism during the Gondwana Period comprising basaltic flows interbedded with sedimentary beds – the Intertrappeans (Rajarao 1987). The Rajmahal traps cover an area of approximately 4100 km^2 and have been interpreted as evolved through decompressional melting of mantle material along the paleocontinental margin of eastern India following rifting of Gondwana around 112 Ma (Mukhopadhyay et al. 1986; Mukhopadhyay 2000). These flood basalts of the Rajmahal Traps and those of the Kerguelen Plateau, and the adjacent regions of the southern Indian Ocean are widely considered to have erupted as a result of lithospheric interaction of the Kerguelen plume during the separation of India and Australia-Antarctica and the fragmentation of Gondwana at 165–133 Ma (Baksi et al. 1987; Storey et al. 1992; Kent et al. 1997, 2002; Coffin et al. 2002; Ghose and Kent 2003). The intertrappean beds are exposed in the southern, central and northern regions of Rajmahal Basin (Figure 1(a)). The Rajmahal Basin has one of the best-developed sequences of the Upper Gondwana sediments that is known for its wealth of plant fossils and being extensively studied. This sequence is represented by the Dubrajpur (Lower Triassic to Lower Cretaceous) and Rajmahal (Lower Cretaceous) formations. The intertrappean beds of Rajmahal Traps have been studied in detail due to its rich plant megafossil assemblage of *Ptilophyllum* flora and other groups of ferns, cycads and conifers (e.g. Sahni 1932, 1948; Sahni and Rao 1933; Rao 1943; Vishnu-Mittre 1956, 1958; Sharma 1967, 1969, 1974, 1997; Sengupta 1988; Banerji 1993, 1995, 2000; Banerji and Jana 1998). Early Triassic to Early Cretaceous spores and pollen were also documented by several workers (e.g. Tiwari et al. 1984; Tripathi et al. 1990, 2013; Baksi et al. 1992; Tiwari and Tripathi 1995; Tripathi 2001, 2002, 2004, 2008; Tripathi and Ray 2006).

Unlike the Upper Gondwana sediments, the Lower Gondwana sediments, represented by the Talchir and Barakar formations are relatively less frequent in the Rajmahal Basin. They are concentrated in the western flanks of the Rajmahal hills in the form of detached outcrops (Figure 1(a)). Whereas in the rest of the basin they are concealed below thick piles of basic volcanics (Rajmahal Traps), Tertiary sediments and Gangetic alluvium, thus obscuring our knowledge about their exact lateral extent. Therefore studies in the Lower Gondwana sequences within the Rajmahal Basin are relatively few and are predominantly based on subsurface sediments. Early Permian palynoassemblages from the Rajmahal Basin have been reported and described by Maheshwari (1967), Srivastava and Maheshwari (1974), Ghosh et al. (1984), Banerjee and D' Rozario (1988), Banerjee and Rozario (1990)). The Talchir palynoflora is particularly least reported from this basin, hitherto comprising of only one report (Banerjee and D' Rozario 1988; Banerjee and Rozario 1990) from the Chuperbhita Coalfield. In this report, the mentioned authors reported three palynoassemblages in ascending order (i) *Plicatipollenites-Parasaccites* (ii) Non striate disaccate *Scheuringipollenites* and (iii) striate disaccate

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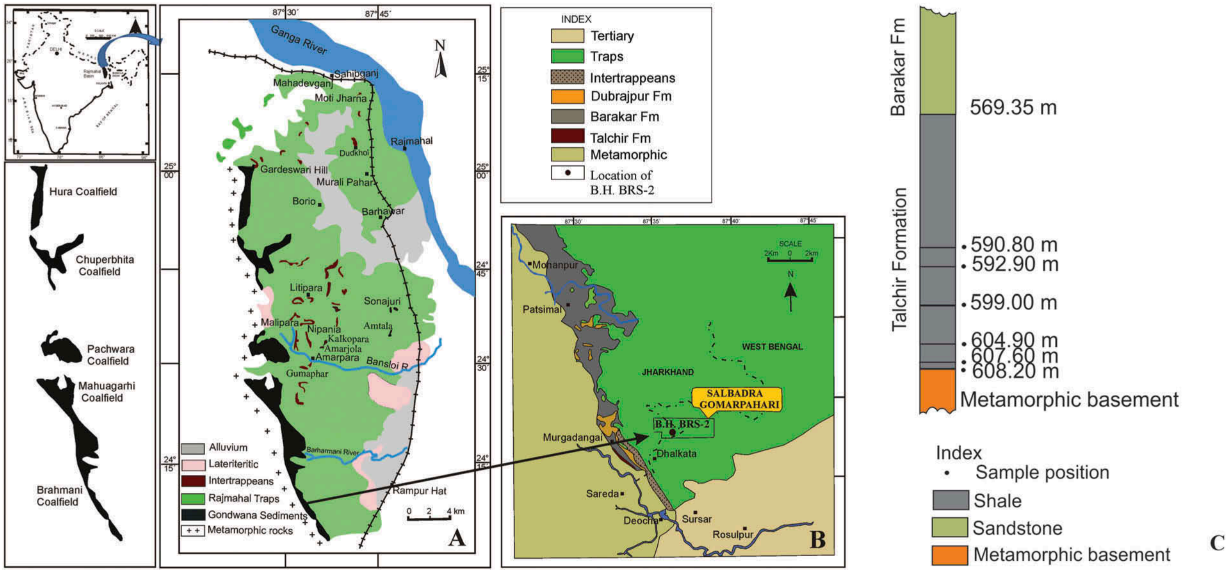

Figure 1. (a) Geological map of the Rajmahal Basin showing the Lower Gondwana Coalfields and the Upper Gondwana formations. (b) Location map of Borehole BRS 2. (c) Stratigraphic succession of the analyzed Borehole BRS 2.

Striatopodocarpites-Striatites. They have not recorded the basal-most assemblage from this coalfield. From the Hura Coalfield they have reported only the early Permian *Scheuringipollenites* assemblage. Therefore, the present contribution is the second report of the palynoflora from the Talchir Formation and the first report from the lowest subsurface interval (590.80–608.20 m) of the borehole BRS-2 located in the east-west trending Salbadra-Gomarpahari region between the Brahmani- Birbhum Coalfield of the Rajmahal Basin. Our results are compared to the zonation of Tiwari and Tripathi (1992), who defined three lower Zones *Potonieisporites neglectus, Plicatipollenites gondwanensis* and *Parasaccites korbaensis* (=*Cannanoropollis janaki*) in the Talchir Formation. An early Permian age was collectively assigned based on the general dominance of monosaccates and the occurrence of Permian marine *Eurydesma* fauna. Furthermore, Gondwanan palynozones, many constrained by absolute ages to both Late Pennsylvanian and Early Permian age, are compared with our assemblages and further discussed together with fossiliferous and stratigraphic information from the studied region.

Geological setting

The Rajmahal Volcanic Province (RVP) is approximately 4300 km^2, located on the northeastern continental margin of the Proterozoic Chotanagpur Gneissic Complex (CGC, Ghose 1983; Chatterjee and Ghose 2011). It is an N-S elongate belt in eastern India bearing the basement of the Gondwana Supergroup and the Rajmahal flood basalts conform the uppermost part of the CGC. The Gondwana sediments of the Rajmahal Basin are part of the North-South trending Rajmahal-Purnea graben which extends over a large area of Jharkhand, and West Bengal states in Eastern India. It is bound by the river Ganges to the North and extends up to the Deewanganj area of Birbhum across the Jharkhand and Bengal boundary to the South (Tripathi 2008). The Gondwana outcrops bearing coal deposits occur in an NNW-SSE trending linear chain along the western flank of Rajmahal hills and are designated from North to South as Hura, Chuperbhita, Pachwara, Mahuagarhi and Brahmani coalfields (Figure 1(a)). The Gondwana sediments crop out in the Birbhum Coalfield of West Bengal State adjacent to the State of Jharkhand. The demarcation of Brahmani and Birbhum coalfields is along the state boundary of Jharkhand and West Bengal. Subsurface data reveals that Gondwana formations, as well as the overlying litho-units in these two coalfields, are physically continuous (unpublished reports of the Geological survey of India). Hence, these two coalfields are sometimes grouped under Birbhum-Brahmani basin. Known extent of Birbhum-Brahmani basin is spread over an area of approximately 200 km^2 (24°02′22″- 24°21′34″N and 87°28′42″ – 87°41′00″E) included in the Survey of India toposheet nos. 72P/6, 72P/7, 72P/10, 72P/11 and 72P/12.

The basal stratigraphic unit of the Rajmahal Basin is the Archean granitic complex; this is overlain by (Table 1) the Talchir, Barakar, Dubrajpur and Rajmahal formations in ascending stratigraphic order (Rajarao 1987). The Upper Gondwana sequences are represented by Dubrajpur and Rajmahal formations. The Rajmahal Formation constitutes traps and Intertrappean beds. The Intertrappean beds are very thin as compared to the thickness of individual lava flow, varying from a few centimeters to about 11m, whereas in subsurface these are up to 100m thick (Tripathi 2008). These sedimentary beds are composed of sandstone, siltstone, arenaceous clay, white and grey color baked shale, carbonaceous shale, tuffite and chert bed. The Lower Gondwana sequence consists of the Permo-Carboniferous Talchir Formation and Permian Barakar Formation (Rajarao 1987).

Material and methods

This study was carried out on borehole BRS-2, located across the interstate boundary of Jharkhand and West Bengal, from which six subsurface samples of shales were processed for palynology. The borehole was drilled in the East-West trending Salbadra-Gomarpahari region located across the state boundary

Table 1. Stratigraphic succession in Salbadra-Gomarpahari region, Brahmani Coalfield (after Rajarao 1987).

Age	Group	Formation	Litho type	Thickness (m) recorded in Salbadra-Gomarpahari sector
Recent/Quaternary		Soil/Alluvium	Yellow to brown sandy, pebbly soil and clay	15.00 (Max. recorded)
		Unconformity (Overlap)		
Early Cretaceous to Late Jurassic	Upper Gondwana	Rajmahal Formation	Basic volcanics and intertrappeans (medium to fine-grained sandstone, dark grey claystone, grey shale and siltstone with oolites)	85.50–165.95
		Unconformity		
Jurassic to Late Triassic	Upper Gondwana	Dubrajpur Formation	Medium-grained sandstone, pebbly sandstone, grey siltstone, mottled shale and claystone	1.25–35.00
		Unconformity (Overlap)		
Early Permian	Lower Gondwana	Barakar Formation	Coarse-grained to pebbly sandstone, very fine to medium-grained feldspathic sandstone, grey shale, carbonaceous shale, and coal seams	171.95–433.60
Early Permian to Late Carboniferous	Lower Gondwana	Talchir Formation	Conglomerate and pebbly sandstone, greenish fine-grained sandstone, greenish shale and siltstone.	1.60–81.90
		Unconformity		
Precambrian		Chhotanagpur Gneissic Complex	Granite gneiss, chlorite biotite schist	-

between Brahmani Coalfield of Jharkhand State and the Birbhum Coalfield of West Bengal State (Figure 1(b,c)). It is entirely covered by Rajmahal volcanics with a thin veneer of soil/alluvium. Therefore in this region the Talchir, Barakar and Dubrajpur formations of the Gondwana Supergroup are above the Precambrian metamorphic basement and below the volcanics of Rajmahal Formation.

Palynological samples were prepared from approximately fifty grams per sample. They were processed using hydrochloric acid for a short time followed by hydrofluoric acid for 24–48 hours. The resultant demineralised residue was oxidized with concentrated nitric acid and then treated with 10% KOH. The residues were sieved through a 400 mesh sieve to isolate the fine fraction and were mounted using polyvinyl alcohol and canada balsam to define their productivity. The slides were analyzed under Olympus BX61 microscope with DP-25 digital camera using Cell A software. The slides are housed at the museum repository of the Birbal Sahni Institute of Palaeosciences, under the codes BSIP slide numbers 16,315–16,325 and England Finder coordinates are used for illustrated specimens. For palynotaxonomic determinations and botanical affinities of taxa large number of illustrated publications were consulted from Gondwana(e.g. Lele and Makada 1972; Lele 1975; Foster 1979; Archangelsky and Gamerro 1979; Balme 1970, 1995; Backhouse 1991; Playford and Dino 2000a, 2000b; Azcuy and Di Pasquo 2000; Di Pasquo and Grader 2012; references therein). Particularly, concerning the name of the lowest *Parasaccites korbaensis* Zone Tiwari and Tripathi (1992), it is replaced by its accepted senior synonym *Cannanoropollis janakii* (see Azcuy and Di Pasquo 2000).

Results

General characteristics of the assemblages

The six samples analyzed were productive. The quali-quantitative analysis revealed dominance of bilateral and radial species of monosaccate pollen grains of the genera *Potonieisporites, Plicatipollenites*, and *Cannanoropollis*. Other monosaccate pollen in lesser frequency include *Stellapollenites, Divarisaccus, Gondwanapollis, Tuberisaccites* and *Circumplicatipollis*. Spores are subordinate to negligible represented by *Punctatisporites, Jayantisporites, Calamospora*, and *Granulatisporites*. Bisaccate pollen grains are almost absent with only a few records of *Limitisporites, Vesicaspora, Scheuringipollenites, Illinites*, and *Lunatisporites*. Both spores and bisaccates make their first appearance at the younger levels between 592.90m and 590.80m. Therefore two assemblages are recognized and distinguished based on the first appearance of taxa. Most of the recorded species are illustrated in Figures 2–4, and the list of species and their distribution at each depth, delimiting the two assemblages is given in Table 2.

Assemblage I

This assemblage is recognized between the depths of 608.20 m-599.00 m. It is characterized by the dominance of monosaccate pollen grains of the Coniferales (*Potonieisporites*) and Cordaitales (*Plicatipollenites* and *Cannanaropollis*) affinity. There is a total absence of spores of either lycophytes, sphenophytes or filicophytes and pollen grains of Pteridospermophyta/Coniferales (Table 2).

Assemblage II

This assemblage is recognized in the overlying interval between the depths of 592.90 m-590.80 m. It is also characterized by a high abundance of monosaccate pollen grains of the genera *Plicatipollenites, Cannanoropollis* and *Potonieisporites* amongst others, but is differentiated from the older assemblage by the first appearance of trilete spores of the lycophyte genus *Jayantisporites* (=*Cristatisporites*), of filico(pterido)phytes *Punctatisporites* and *Granulatisporites* and the first appearance although of rare occurrence, of *Limitisporites, Scheuringipollenites, Vesicaspora, Illinites*, and *Lunatisporites*, related to Coniferales/Pteridospermophyta (Table 2).

Discussion

Tiwari and Tripathi (1992) have synthesized the data from palynologically well studied Permian-Mesozoic sequences

Figure 2. Stratigraphically significant forms of Assemblage I from Borehole BRS-2.
1. *Potonieisporites lelei* Maheshwari, BSIP.16319, EF: P.58.4
2,7. *Potonieisporites novicus* Bharadwaj emend. Poort and Veld
2. BSIP.16322, EF: A.43.3
7. BSIP. 16320, EF: X.60
3. *Potonieisporites congoensis* Bose and Maheshwari, BSIP 16318, EF: Q.45.3
4. *Potonieisporites lelei* Maheshwari, BSIP. 16325, EF:W.56.3
5. *Potonieisporites neglectus* Potonié & Lele, BSIP. 16322, EF: V.34.3
6. *Potonieisporites magnus* Lele and Karim, BSIP. 16321, EF: O.37.3
8,9,10. *Potonieisporites barrelis* Tiwari 1965
8. BSIP. 16317, EF: R.28
9.BSIP. 16322, EF: F.38.1
10.BSIP. 16318, EF: T.33
11. *Cannanoropollis triangularis* (Mehta) Bose and Maheshwari, BSIP. 16319, EF: W.38.4
12. *Plicatipollenites gondwanensis* (Balme and Hennelly) Lele, BSIP. 16321, EF:X.37
13. *Gondwanapollis cf.G.frenguellii* (Césari) Gutierrez, BSIP. 16322, EF: F.49.4
14. *Cannanoropollis janaki* Potonié & Sah, BSIP. 16325, EF: S.63
15. *Circumplicatipollis stigmatus* (Lele and Karim) Ottone and Azcuy, BSIP. 16318, EF: R.46.1

from different Gondwana basins of India. They recognized 20 Assemblage zones and 30 acme zones based on the whole composition and LADs and FADs of selected species. Their three lower Assemblage Zones *Potonieisporites neglectus, Plicatipollenites gondwanensis* and *Cannanoropollis janakii* (=*Parasaccites korbaensis*) are defined in the Talchir Formation of India, and they were assigned to the Early Permian based on the general dominance of monosaccates and the associated occurrence of Permian marine *Eurydesma* fauna.

A comparison with our assemblages allow us to correlate the Assemblage I to the *P. neglectus* Zone and the Assemblage II to the *Plicatipollenites gondwanensis*. A Permian faunal assemblage was found in association with the younger *P.*

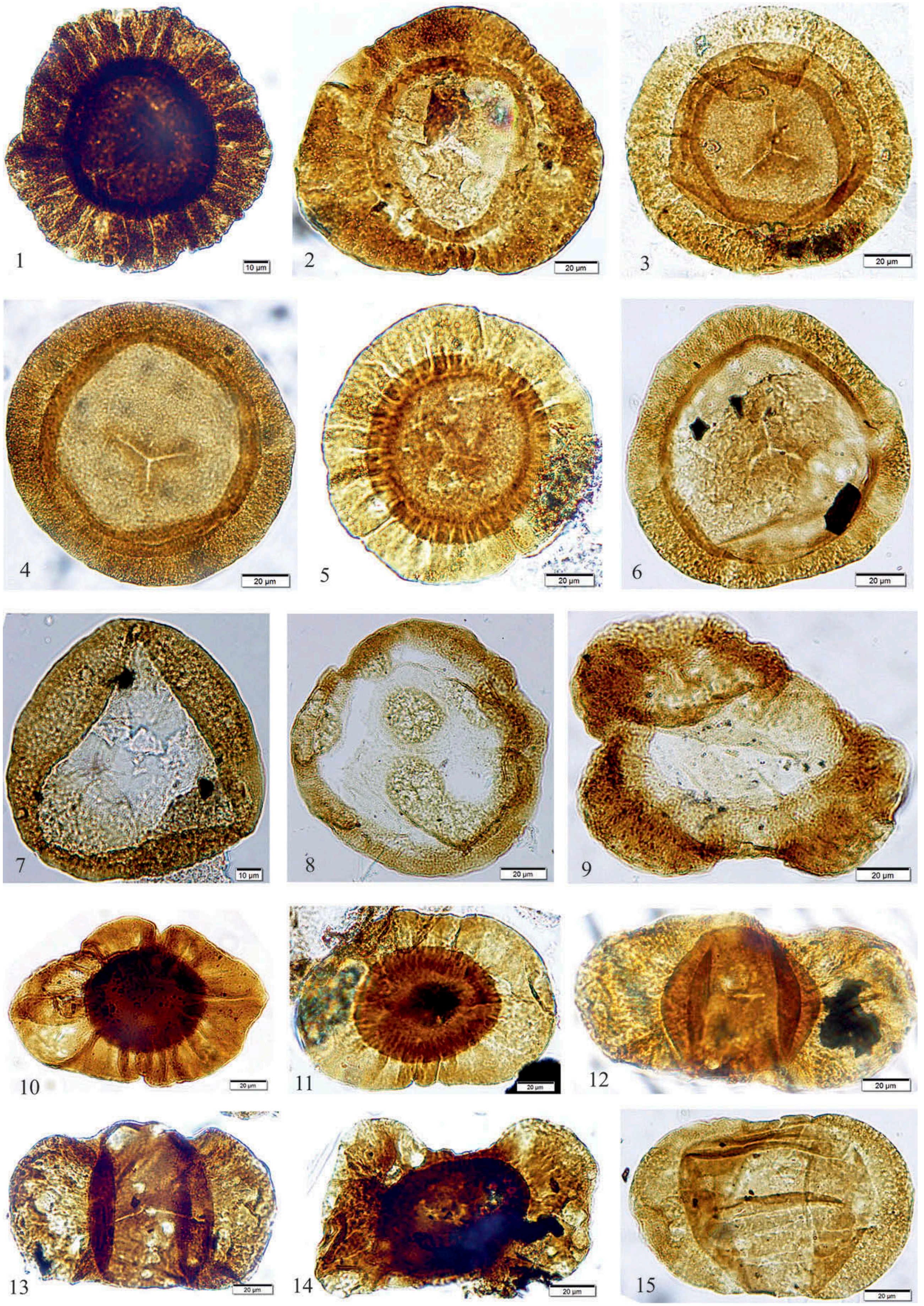

Figure 3. Stratigraphically significant forms from Assemblage I and II of Borehole BRS-2.

1. *Cannanoropollis densus* (Lele) Bose and Maheshwari, BSIP. 16323, EF: N.55-2.
2, 6. *Plicatipollenites trigonalis* Lele.
2. BSIP. 16324, EF: G.32-2.
6. BSIP. 16318, EF: F.59
3. *Plicatipollenites gondwanensis* (Balme and Hennelly) Lele, BSIP. 16319, EF: Q.45-1
4,5. *Plicatipollenites malabarensis* (Potonié & Sah) Foster.
4. BSIP. 16319, EF: F.33-2
5. BSIP. 16324, EF: U.56
7. *Stellapollenites talchirensis* Lele BSIP. 16324, EF: R.54-4
8. *Tuberisaccatus lobatus* Lele and Makada, BSIP. 16318, EF: M.47-3
9. *Trochosporites* sp. BSIP. 16318, EF: M.62-1
10,11. *Costatacyclus crenatus* (Felix & Burbridge) Urban
10. BSIP. 16321, EF: G.40-2
11. BSIP. 16324, EF: L.34-1
12. *Limitisporites hexagonalis* Bose and Maheshwari, BSIP. 16319, EF: N.36
13. *Limitisporites rectus* Leschik, BSIP. 16315, EF: S.65-4
14. *Caheniasaccites flavatus* (Bose and Kar) Azcuy & di Pasquo, BSIP. 16315, EF: K.4
15. *Illinites talchirensis* (Lele and makada) Azcuy, Mercedes, Ampuero, BSIP. 16318, EF: V.36.2

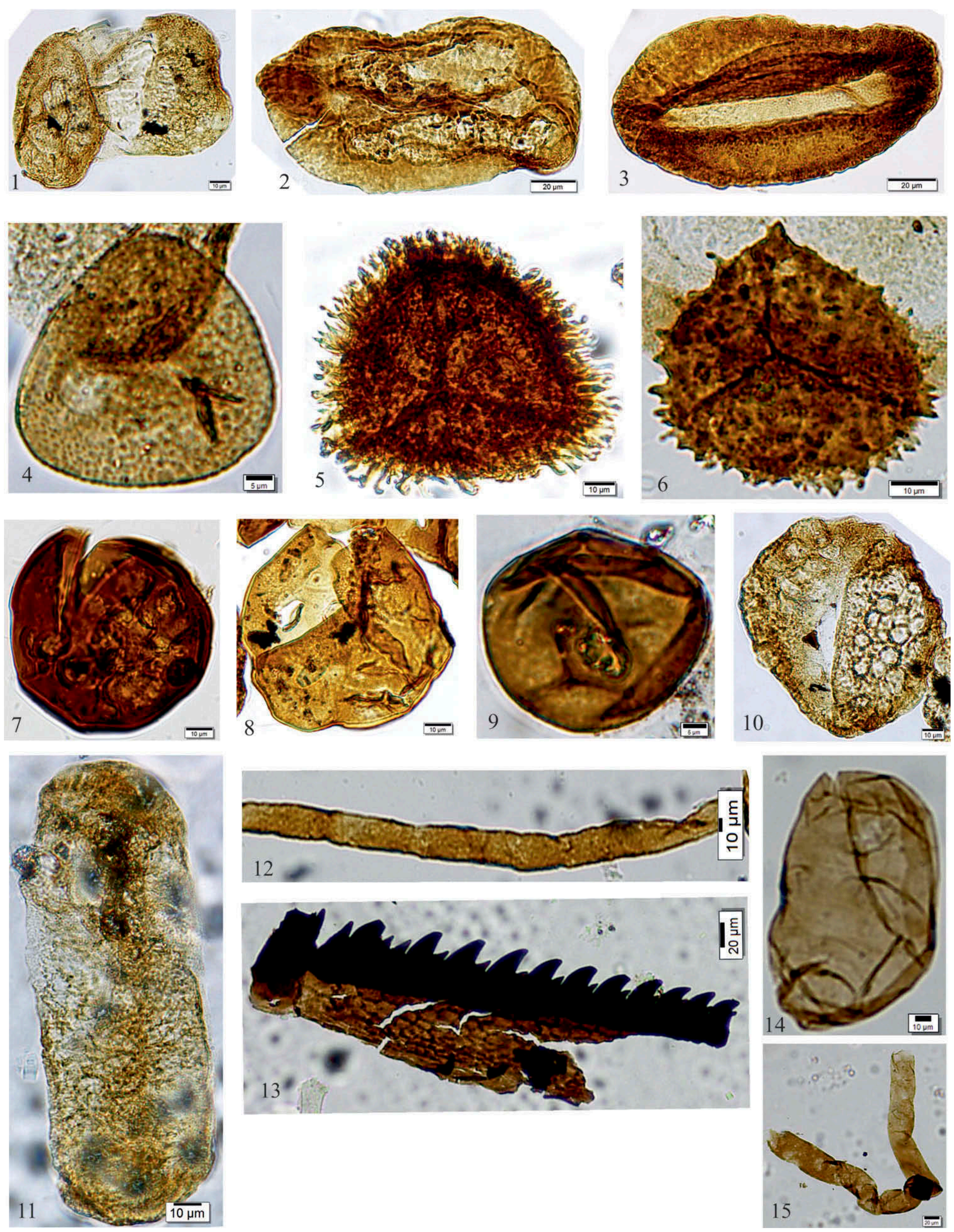

Figure 4. Stratigraphically significant forms of Assemblage II of Borehole BRS-2.
1. *Lunatisporites varisectus* Archangelsky and Gamerro, BSIP. 16318, EF: L.34
2. *Divarisaccus strengeri* Bose and Kar 1966, BSIP. 16325, EF: L.34
3. *Divarisaccus lelei* Venkatachala and Kar 1966, BSIP. 16318, EF: E.41-2

4. *Granulatisporites austroamericanus* Archangelsky and Gamerro, BSIP. 16317, EF: K.31
5. *Jayantisporites pseudozonatus* Lele and Makada 1972, BSIP. 16318, EF: G.31
6. *Jayantisporites conatus* Lele and Makada 1972, BSIP. 16317, EF: P.35
7, 8. *Punctatisporites gretensis* Balme and Hennelly
7. BSIP. 16316, EF: T.52
8. BSIP. 16315, EF: Q.56
9. *Calamospora liquida* Kosanke 1950, BSIP. 16318, EF: R.39-4
10. *Scheuringipollenites maximus* (Hart) Tiwari 1973, BSIP. 16318, EF: M.59
11. *Navifusa* sp. . BSIP. 16318, EF: S.40-4
12. Fungal hyphae, BSIP. 16318, M.44
13. *Scolecodont*, BSIP. 16318, U.44.2
14. *Leiosphaerid* sp. BSIP. 16320, EF: T.34-1
15. *Reduviasporonites chalastus* (Foster) Elsik BSIP. 16321, EF: P.52

gondwanensis Assemblage Zone but not in association with the oldest *Potonieisporites neglectus* Assemblage Zone. Hence, we establish for both *P.neglectus* and our Assemblage I an older age akin to the latest Pennsylvanian. This is also supported by the absence of Glossopteridales from the Lower Talchir Formation and the stratigraphic position of its reference section that corresponds to the siltstones above the oldest basal boulder beds overlying the Precambrian basement at the Dudhi river section, west Bokaro Coalfield. Whereas an early Permian age is confirmed for the Assemblage II and *P. gondwanensis* Assemblage Zone.

Age and correlation in a global context

Gondwana sedimentation in India began by the initial relaxation of the Pangean platform near the end of the Carboniferous Period, leading to glacially scoured depressions, which formed broad depocenters for the accumulation of rock debris released from melting glaciers and ice sheets (Veevers and Tewari 1995). Therefore the Gondwana succession in India ranges from the upper Carboniferous to Lower Cretaceous and it is followed by its break up (Smith 1963; Rajarao 1987; Veevers and Tewari 1995; Veevers 2004; Murkute 2015).

Table 2. Distribution of taxa at each depth in borehole BRS2, delimiting the two assemblages. Note: The numbers correspond to percentages except in the sample (607.60).

Sl.no	Name of the taxa	608.20	607.60	604.90	599.00	592.0	590.80
1	*Potonieisporites neglectus*	2		2.5	3		0.5
2	*Potonieisporites magnus*	2	1 grain	2.5	1	2.5	2.5
3	*Potonieisporites barrelis*	1.5		2	3	3	2.5
4	*Potonieisporites congoensis*		1 grain		2.5	5	5
5	*Potonieisporites lelei*	2		1	1	1.5	5
6	*Potonieisporites densus*		2 grains		0.5		0.5
7	*Potonieisporites novicus*				5		2.5
8	*Plicatipollenites gondwanensis*	15	5 grains	15	11	3.5	6.5
9	*Plicatipollenites malabarensis*	18	8 grains	15	12.5	10	10
10	*Plicatipollenites trigonalis*		5 grains	2		2	5
11	*Cannanoropollis janaki*	13	7 grains	20	20	11	15
12	*Cannanoropollis trigonalis*	2.5	1 grain				
13	*Cannanoropollis mehtae*	2.5		0.5	5		2.5
14	*Cannanoropollis triangularis*	2.5		2.5	1	0.5	2.5
15	*Cannanoropollis densus*	2.5	2 grains	2.5			
16	*Divarisaccus lelei*	15.5	2 grains	15	10	7.5	6
17	*Divarisaccus strengeri*	4.5	1 grain	7.5	5	2.5	2.5
18	*Circumplicatipollis stigmatus*	2.5		5	12	10	6.5
19	*Costatacyclus crenatus*	1		1.5			
20	*Caheniasaccites flavatus*					2.5	2.5
21	*Gondwanapollis cf. frenguelli*	1					
22	*Stellapollenites talchirensis*	2					
23	*Tuberisaccites lobatus*	5				0.5	3
24	*Punctatisporites gretensis*					1	2.5
25	*Calamospora liquida*					0.5	
26	*Jayantisporites conatus*					7	5
27	*Jayantisporites pseudozonatus*					5	3.5
28	*Granulatisporites austroamericanus*					1	
29	*Limitisporites rectus*					7	3
30	*Limitisporites hexagonalis*					5	3
31	*Illinites talchirensis*					0.5	
32	*Lunatisporites varisectus*					0.5	
33	*Scheuringipollenites maximus*					1	
34	*Vesicaspora* sp.					0.5	
35	*Trochosporites* sp.					0.5	
36	*Navifusa* sp.					2	
37	*Scolecodont*					0.5	
38	*Reduviasporonites chalastus*					0.5	
39	*Fungal hyphae*					1	
40	*Indet.monosacs*	5	5	5.5	7.5	4.5	2.5
		Assemblage 1 Late Pennsylvanian				Assemblage 2 Asselian	

The Indian Gondwana sequences were palynologically considered as ranging from early Permian on the basis of the occurrences of the Permian marine *Eurydesma* fauna interbedded with rich monosaccate pollen grain assemblages in the Talchir Formation (Tiwari and Tripathi 1988, 1992; Venkatachala and Tiwari 1988). Moreover, hitherto in Indian palynozonation there has been a tendency to describe each of the lithological subdivisions of the Gondwana sequence separately and describe assemblages that are confined to and based on the litho-stratigraphic subdivision, making it difficult to compare and correlate in terms of species ranges. This has been pointed out by Truswell (1980) who stated that-"… *In India there has been a tendency to describe each of the lithological subdivisions of the Gondwana sequence separately; thus we have accounts of the palynology of the Talchir, Karharbari, Barakar, Barren Measures and Raniganj Stages, but few papers that treat the stratigraphic ranges of species against a framework of the entire sequence. This has made for difficulties in intercontinental correlation.*" And also by Modie and Le Herisse´ (2009) who stated that *"Correlation with the Gondwana Sequence of India is overwhelmingly limited despite several decades of palynological studies that generated a plethora of data on morphotaxonomy and palynostratigraphy. Most palynostratigraphic studies involve quantitative analyses at the genus level and describe assemblages that are confined to and based on the litho-stratigraphic subdivision, making it difficult to compare and correlate in terms of species ranges.*" Hence there is so much hesitance in taking the lower range of the basalmost assemblage into the Late Pennsylvanian, although there are palynological similarities with the oldest assemblage from the basal Talchir of India and other Late Pennsylvanian assemblages across Gondwana (i.e. abundance of monosaccates like *Potonieisporites, Plicatipollenites, Cannanoropollis* along with evident absence of Permian markers). In this work we are reinforcing the significance of considering the range of species that facilitates intercontinental correlation, which was hitherto hampered.

Due to the ubiquity of palynomorphs in Late Paleozoic successions and relatively less frequently interbedded datable igneous rocks, chronostratigraphic correlations in Gondwanan studies were attempted on palynomorphs (e.g. Backhouse 1991; Lindström 1995a, 1995b; Playford and Dino 2000b; Di Pasquo 2003; Souza 2006; Stephenson 2008; Vergel 2008; Di Pasquo et al. 2010, 2015; Césari et al. 2011).Correlation relied on palynology was also combined with information from marine and plant index fossils especially when they were documented from the same successions (e.g. Azcuy et al. 2007; Cisterna et al. 2011; Jha et al. 2014; Kavali and Jha 2014; Murthy et al. 2015; Bernardes-de-Oliveira et al. 2016; Taboada et al. 2016; Di Pasquo et al. 2017). However, as pointed out by Stephenson (2008) and Stephenson (2008) among others, correlations across Gondwana are difficult mainly due to differences in stratigraphic and taxonomic methods and documentation of palynological data from farfield areas across Gondwana. Biozones in general represent long intervals of more than 2 Ma., so diachronisms between similar palynoassemblages are underestimate unless absolute ages or relative ages based on more accurate fossiliferous groups (e.g. conodonts, ammonoids) are provided (see Di Pasquo et al. 2015). The new information obtained from lowest Talchir Formation is used to discuss below and resolve to a certain degree, the differences that persisted hitherto regarding the age of the basalmost Gondwanan floras from India. The palynoflora from this study is analyzed from its chronological point of view in the context of well constrained Gondwanan biozones with absolute ages as well as marine faunal zones and limitations are also evaluated. A critical analysis of the composition of these assemblage zones, their reference horizons, corresponding lithofacies and the correlation of their constituent elements across Gondwana is addressed below.

Assemblage I

The Indian Gondwana sequences were palynologically considered as ranging from early Permian on the basis of the occurrences of the Permian marine *Eurydesma* fauna interbedded with rich monosaccate pollen grain assemblages in the Talchir Formation (Tiwari and Tripathi 1988, 1992; Venkatachala and Tiwari 1988; Jha et al. 2018). However, the marine *Eurydesma* fauna was found to be associated with the younger *Plicatipollenites gondwanensis* Assemblage Zone and absent in the oldest basal *Potonieisporites neglectus* Assemblage Zone.

Veevers and Tewari (1995) in their classic work on the Gondwana Master Basin of Peninsular India, based their time slices on the palynozones of Tiwari and Tripathi (1988). Interestingly, they correlated the Palynocomposition IA of the basal Talchir Formation with the Late Pennsylvanian (Kasimovian-Ghezelian) Stage 1 of Western Australia (Powis 1984). The *Potonieisporites neglectus* Assemblage Zone of Tiwari and Tripathi (1992) corresponds to the oldest segment of Composition IA of *Plicatipollenites-Parasaccites* Zone of Tiwari and Tripathi (1988). It is the least diversified characterized by the dominance of girdling radial and bilateral monosaccates *Plicatipollenites, Cannanoropollis Potonieisporites*, the rare occurrence of *Verrucosiporites* type spores and absence of striate bisaccates. The reference section of the oldest *Potonieisporites neglectus* AZ of Tiwari and Tripathi (1992) corresponds to the siltstone unit above the first boulder bed at the metamorphic basement from the Dudhi river section in West Bokaro Coalfield Bihar (Sample no B19/662 and B17/662, Lele 1975).These boulder beds and associated sediments indicate initiation of sedimentation by melting glaciers (Smith 1963; Veevers and Tewari 1995). Srivastava and Agnihotri (2010) in their review from the Lower Gondwana sequences showed that there are no records of glossopterids in the Lower Talchir sequences from Indian basins except for one species of *Gangamopteris cyclopteroides* by Surange and Lele (1955) from the Talchir needle shale of Giridih Coalfield, Bihar. But its stratigraphic position is doubtful. The authors of that work could not ascertain the exact stratigraphic position of the fossiliferous spot above the boulder bed, as the needle shales were not in contact with the boulder bed but they were exposed at a distance of two furlongs away from the fossiliferous spot. The height of these needle shales was about ca.m 4–7 m but its stratigraphic position remains doubtful.

The Assemblage I herein studied is correlated to the *Potonieisporites neglectus* AZ of Tiwari and Tripathi (1992) due to the abundance of monosaccates and the absence of spores and bisaccates (see Table 3). A latest Pennsylvanian age is akin to the Assemblage I and the *Potonieisporites neglectus* Assemblage-Zone of Tiwari and Tripathi (1992) of the lowest Talchir Formation.This result does not follow the conventional concept of the Indian workers that the abundance of monosaccates marks the beginning of the Permian in India (Tiwari and Tripathi 1988, 1992; references therein). A

Table 3. Correlation of the Assemblage I and II with the basal three zones of Tiwari and Tripathi (1992). Note: A is correlatable with C; B is correlatable with D.

	A	B	C	D	E
Potonieisporites neglectus	X	X	X	X	X
Potonieisporites magnus	X		X	X	
Potonieisporites barrelis	X	X	X	X	
Potonieisporites congoensis	X	X	X	X	
Potonieisporites lelei		X	X	X	X
Potonieisporites densus	X	X	X	X	X
Potonieisporites novicus	X	X	X	X	
Plicatipollenites gondwanensis	X	X	X	X	
Plicatipollenites malabarensis	X	X	X	X	X
Plicatipollenites trigonalis	X	X		X	X
Cannanoropollis (=*Parasaccites*) *janakii*	X	X	X	X	X
Cannanoropollis (=*Parasaccites*) *trigonalis*	X	X	X	X	X
Cannanoropollis (=*Parasaccites*) *mehtae*	X	X	X	X	X
Cannanoropollis (=*Parasaccites*) *triangularis*	X	X	X	X	X
Cannanoropollis (=*Parasaccites*) *densus*	X	X	X	X	X
Divarisaccus lelei	X	X			
Divarisaccus strengeri	X	X			
Circumplicatipollis stigmatus	X	X	X	X	X
Stellapollenites talchirensis	X	X			
Gondwanapollis cf. frenguelli	X				
Tuberisaccites tuberculatus	X			X	X
Costatacyclus crenatus	X				X
Caheniasaccites flavatus		X			X
Punctatisporites gretensis		X		X	
Calamospora liquida		X			X
Jayantisporites conatus		X		X	X
Jayantisporites pseudozonatus		X			X
Granulatisporites austroamericanus		X			
Limitisporites rectus		X		X	
Limitisporites hexagonalis		X		X	
Illinites talchirensis		X		X	X
Lunatisporites varisectus		X			
Scheuringipollenites maximus		X			
Vesicaspora sp.		X			
Trochosporites sp.		X			
Cyclogranisporites sp.			X		
Verrucosisporites cf. *donarii*			X		
Apiculatisporis sp.			X		
Verrucosisporites sp.				X	
Punctatisporites minutus					X
Granulatisporites sp.					X
Cyclogranisporites plicatus					X
Verrucosisporites varius					X
Horriditriletes novus					X
Divarisaccus scorteus					X
Crucisaccites latisulcatus					X
Vestigisporites diffusus					X
Platysaccus papilionis					X
Alisporites opii					X
Vesicaspora breckmanii					X
Vesicaspora crassa					X
Scheruringipollenites maximus					X
Illinites ovatus					X
Protohaploxypinus (=*Faunipollenites*) *varius*					X
Protohaploxypinus (=*Faunipollenites*) *goraiensis*					X
Lahirites singularis					X
Striasulcites sp.					X

A-Assemblage I of this study

B-Assemblage II of this study

C-Assemblage of the *Potonieisporites neglectus* Assemblage-Zone of Tiwari and Tripathi (1992) from its Reference section- Lele (1975)- Dudhi River Section; Sample nos. B.17/662, B.19/662. Siltstone units above the first boulder bed at the metamorphic basement, West Bokaro Coalfield, Bihar (as considered by Tiwari and Tripathi 1992).

D- Assemblage of the *Plicatipollenites gondwanensis* Assemblage- Zone of Tiwari and Tripathi from its Reference section- Lele (1975)- Lele (1975)- Dudhi River Section; Sample nos. B.9/662 Siltstone units above the last boulder bed in the section, West Bokaro Coalfield, Bihar (Tiwari and Tripathi 1992).

E-Assemblage of the *Parasaccites korbaensis** Assemblage-Zone of Tiwari and Tripathi (1992) from its Reference sLele and Makada (1972), Section exposed at the Patharjore nala, Jayanti Coalfield Bihar (Tiwari and Tripathi 1992).

(*Note: Some of the species in the reference section are designated by different names (* *P. korbaensis* = *Cannanoropollis janakii*, see Azcuy and Di Pasquo 2000), which after observation in their respective plates have been considered similar to those listed here).

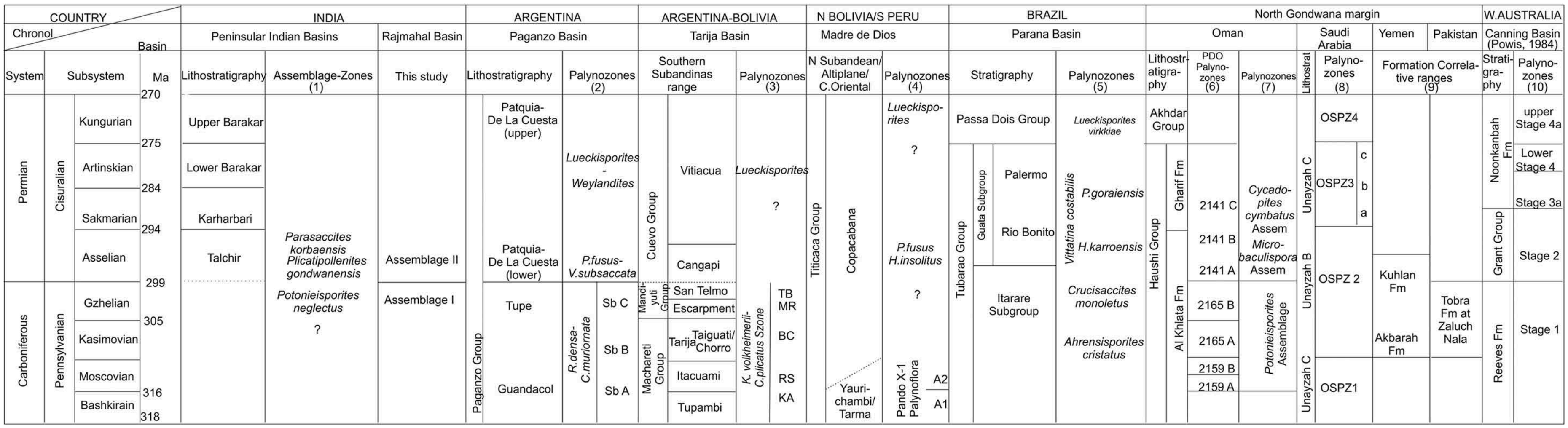

Figure 5. Global correlation of the Assemblage I of this study and the *Potonieisporites neglectus* Assemblage Zone of Tiwari and Tripathi (1992) with the radiometrically dated Late Pennsylvanian assemblages, and correlation of Assemblage II of this study and *Plicatipollenites gondwannesis* AZ of Tiwari and Tripathi (1992) with the early Cisuralian palynofloras from selected regions across Gondwana. (**1**. Tiwari and Tripathi 1992; **2**. Césari et al. 2011; **3**. Di Pasquo 2003; **4**., 2009; **5**. Souza 2006; **6**. Penney et al. 2008; **7**. Love 1994; **8**. Stephenson et al. 2003; **9**., 2013; **10**. Powis 1984). For further references refer text. Dotted lines indicate doubtful boundaries.

Potonieisporites dominant assemblage has also been reported by Lele (1984) from the Talchir siltstones and clasts associated with the basal boulder beds which unconformably overlie the Proterozoic Penganga limestones and dolomites near Irai in Maharahtra State, Central India. This assemblage has been correlated with the Late Pennsylvanian Stage 1 of Australia (Kemp et al. 1977). Smith (1963) attributed an upper Carboniferous age to the these Talchir boulder beds at Irai. Therefore, abundance of monosaccates by themselves cannot be taken as the base for the Permian in India since their global occurrence dates back to their first appearance at the Serpukhovian-Bashkirian in palynofloras around the World, some of which have been radiometrically dated (see Azcuy 1975; Di Pasquo 2002; Vergel et al. 2015; Di Pasquo et al. 2016; Valdez et al. 2017). A further discussion on this biological event is out of the scope of this work.

Neither the appearance of striate bisaccates can be considered as Permian indicators in India, unless diagnostic species of Permian sequences across Gondwana are recorded (e.g. *Vittatina saccata, V. subsaccata, V. costabilis, Pakhapites fusus, P. ovatus, Lunatisporites noviaulensis, L. pellucidus*, and species of *Weylandites, Striatoabieites*).

Therefore, the non-deposition or erosion of the oldest sequences in the Indian Peninsula (Mukhopadhyay et al. 2010), the record of the *Eurydesma* Fauna, and the *Glossopteris* Flora, are not arguments to date the whole Talchir Formation as Permian, and especially if those taxa are not recorded in the lower intervals correlatable to *Potonieisporites neglectus* Assemblage Zone.

A correlation of the Assemblage I and *P. neglectus* AZ to palynofloras of the Late Pennsylvanian from South America and elsewhere can be established based on the dominance of monosaccate grains (e.g. Kemp et al. 1977; Zhou 1994; Ouyang 1996; Di Pasquo and Azcuy 1997; Playford and Dino 2000a, 2000b; Césari and Gutiérrez 2001; Di Pasquo 2002, 2007, 2009; Di Pasquo et al. 2003, 2010, 2017; Melo and Loboziak 2003; Souza 2006; Penney et al. 2008; Vergel 2008; Stephenson 2009; Pérez Loinaze et al. 2014) (Figure 5).

Assemblage II

Assemblage II is characterized by the dominance of *Plicatipollenites* and subdominance of *Cannanoropollis* (see Table 2) and it is similar to the palynoassemblage from Manendragarh beds of the Lower Talchir Formation (Figure 6), State of Madhya Pradesh in Central India (Lele and Chandra 1972). Both palynoassemblages are correlated to the *Plicatipollenites gondwanensis* Assemblage Zone of Tiwari and Tripathi (1992), which are dominated by monosaccates but qualitatively more diversified in spores and pollen grain species of *Protohaploxypinus, Limitisporites, Jayantisporites* among others (see Table 2 of Tiwari and Tripathi 1992). The reference section of this assemblage corresponds to the siltstone unit above the second and younger boulder bed at the Dudhi river section in West Bokaro Coalfield Bihar (Sample no. B9/662, Lele 1975).

The overlying *Cannanoropollis janakii* (=*Parasaccites korbaensis*) AZ, is also dominated by monosaccates but exhibits a further diversified flora, with new inceptions of pteridophytic apiculate and lycopsid spores and ginkgo-cycadoid pollen grains (see Table 2 of Tiwari and Tripathi 1992). The first occurrence of *Divarisaccus lelei* marks the base of this zone and the oldest occurrence of *Crucisaccites monoletus* marks the top of this zone. The reference section of this zone is the Patharjore Nala section in the Jayanti Coalfield, Bihar, which are also siltstones above younger boulder beds (Lele and Makada 1972).The recurrence of the boulder beds and associated glacigene sediments indicate advance and retreat of glaciers leading to interglacial phases. These interglacial phases favored the growth of vegetation (Smith 1963; Veevers and Tewari 1995).

These palynoassemblages share few of the diagnostic taxa of the Early Cisuralian palynofloras that are characterized

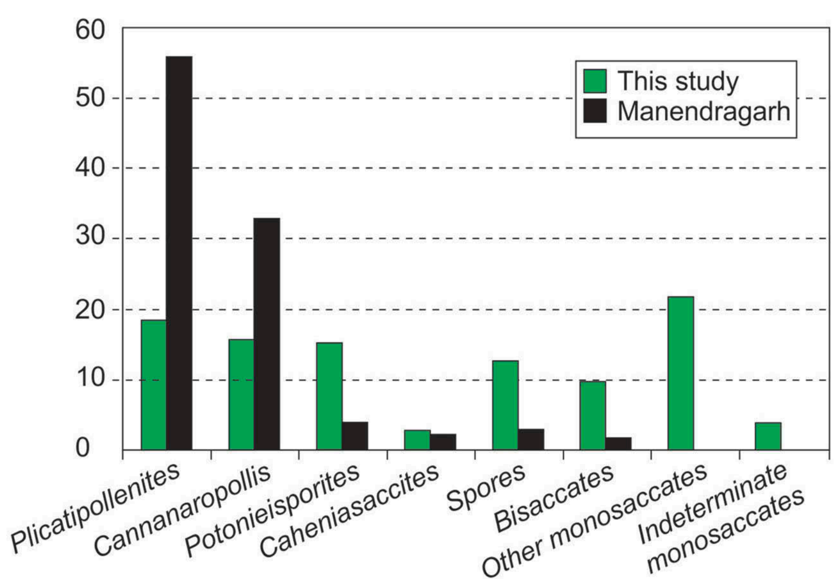

Figure 6. Correlation of the Assemblage II of this study with the Assemblage from Manendragarh (Lele and Chandra 1972), where both show dominance of *Plicatipollenites* and subdominance of *Cannanoropollis*. However the Assemblage II of this study records other species, which are absent in the Manendragarh assemblage likely attributed to ecological differences in the two regions.

by bisaccate taeniate pollen grains (*Protohaploxypinus, Hamiapollenites, Striatopodocarpites*), plicates (*Pakhapites, Vittatina, Marsupipollenites*) and some spores (e.g. *Converrucosisporites confluens*, and several species of *Horriditriletes*). These taxa are especially recorded in South America (Playford and Dino 2000a, 2000b; Césari and Gutiérrez 2001; Souza 2006; Di Pasquo et al. 2010, 2017; Di Pasquo and Grader 2012; Pérez Loinaze et al. 2014), Africa (Falcon 1975; Anderson 1977; MacRae 1988; Semkiwa et al. 1998, 2003; Millsteed 1999; Modie and Le Herisse´ 2009; Stephenson 2015), Arabia and Pakistan (Besems and Schuurman 1987; Love 1994; Stephenson and Filatoff 2000; Stephenson and Osterloff 2002; Stephenson et al. 2003, 2013; Stephenson 2006, 2008; Penney et al. 2008; Jan et al. 2009; Jan and Stephenson 2011), Australia (Evans 1969, Kemp et al. 1977; Backhouse 1991; Jones and Truswell 1992) and Antarctica (e.g. Lindstrom 1995a, 1995b, 1996). The absence of these taxa in the Assemblage I of the present study and in the *Potonieisporites neglectus* AZ of Tiwari and Tripathi (1992) reinforce that they are older.

The upper Talchir Formation is akin to the Early Cisuralian by the documentation of diverse species of *Gangamopteirs* and few species of *Glossopteris* (see Table 3 of Srivastava and Agnihotri 2010). This age is also given to the Umaria beds from the upper Talchir Formation that have yielded only two pollen grains and marine palynomorphs as a rich assemblage of acritarchs (Lele and Chandra 1972), and to the Manendragarh assemblage in which the palynoassemblages are in association with the Permian marine *Eurydesma* fauna. Occurrences of the *Eurydesma* fauna are known across the W-E transgondwanan marine connections between South America, Africa, Pakistan, Australia (Pascoe 1959; Runnegar 1979; Azcuy et al. 2007; Stollhofen et al. 2008; Jan and Stephenson 2011; Mory and Haig 2011; Neves et al. 2014a; Taboada et al. 2016) and the peninsular India (Sinor 1923; Ghosh 1954; Sahni and Dutta 1959; Mishra et al. 1961; Shah 1963; Dutt 1965; Venkatachala and Rawat 1984; Venkatachala and Tiwari 1988) and beyond, toward the Cimmerian region (Dickins and Thomas 1959; Archbold 1998, 2000; among others) indicating a Gondwanawide transgression by a major postglacial eustatic rise in sea-level (Dickins and Thomas 1959; Dickins 1997), which resulted from the collapse of the main Gondwana Ice Sheets (Veevers and Powell 1987). A 'V' shaped proto-rift system was envisaged by Stollhofen et al. (2000), (2008)) where the probable sea way passage for the *Eurydesma* transgression was proposed between the South Africa-Malvinas/Falklands-Agulhas plateau and the Antarctic detached southern Patagonia (Deseado Massif) (Ramos and Naipauer 2014) before its collision with South Africa (Lindeque et al. 2011) and the pre-drifted Ellsworth mountain terrane (Elliot et al. 2016). The rift continued northeastward to western Australia including the Perth,Carnarvon and Canning basins (Biswas 1999; Cawood and Nemchin 2000; Harrowfield et al. 2005) and extended further to the transgondwanan Cimmerian continent during the Asselian-early Sakmarian. The Central-eastern Peninsular India subsidiary linear rift basins, such as the Koel-Damodar, Son-Mahanadi, Pranhita-Godavari and Satpura basins document the marine incursion of the *Eurydesma* transgression (Casshyap and Tewari 1987; Wopfner and Casshyap 1997; Ghosh 2003) forming the eastern branch of the main proto rift. The age of the whole *Eurydesma* fauna is radiometrically constrained spanning the post Gzhelian earliest Asselian (radiometric ages from the Hardap shale Member in Africa) until Kungurian times in eastern Australia, SE Gondwana, due to persistent cold paleoclimatic conditions (Dickins 1978).

The *Eurydesma* bearing Taciba Formation of the Paraná Basin in Brazil (Figure 7) has been radiometrically constrained to pre Sakmarian times based on the radiometric

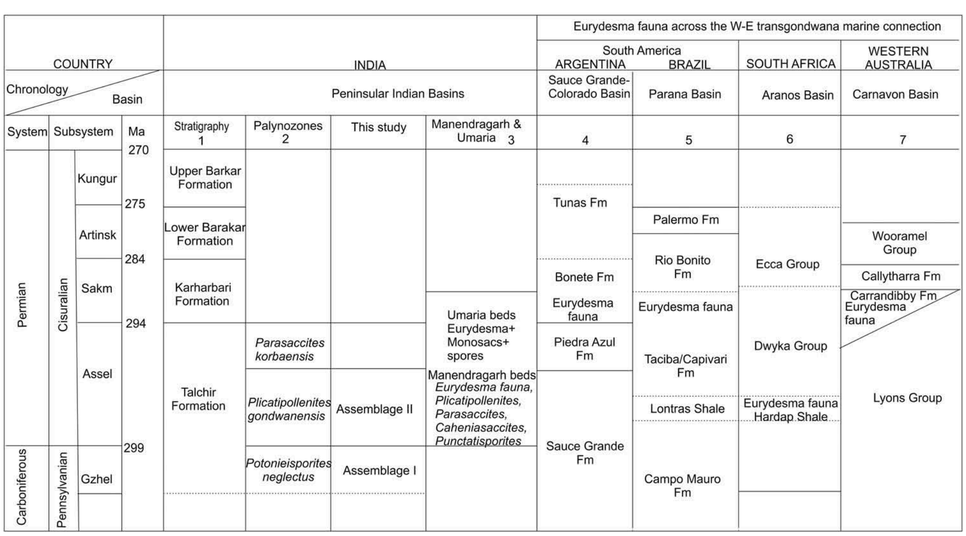

Figure 7. Correlation of the Assemblage II with the assemblage from Manendragarh beds found in association with *Eurydesma* fauna and with the lithostratigraphic units of selected basins from West and East Gondwana containing diachronic occurrences of *Eurydesma*. The older assemblage is constrained to post Gzhelian times and the younger to late Asselian -early Sakmarian. In India, the Manendragarh assemblage contains the older Eurydesma assemblage, while the Umaria has the younger assemblage. See in the text explanations for the correlation between the assemblage I and *Potonieisporites neglectus* assemblage zone with Late Pennsylvanian palynofloras in Gondwana. (**1**. Mukhopadhyay et al., 2010, **2**. Tiwari and Tripathi 1992; **3**. Lele and Chandra 1972; **4**. Neves et al., 2014, **5**. Taboada et al. 2016; **6**. Dickins 1985; **7**. Mory and Haig 2011). Dotted lines indicate doubtful boundaries. (modified from Taboada et al. 2016).

age of 291 ± 1.2 Ma, obtained from tonsteins interbedded in coal seams of the overlying Rio Bonito Formation, which can be applied to the coeval fauna of the Bonete Formation of Sauce-Grande Colorado Basin of Argentina (Neves et al. 2014). In western Australia (eastern Gondwana), the *Eurydesma* fauna is recorded throughout the upper part of the glacial-related Lyons Group and the postglacial Carrandibby Formation (Mory and Haig 2011), whose age interval has been constrained to late Sakmarian by ammonoids (Archbold 1999, 2001; Leonova 1999, 2011; Haig et al. 2014). Taboada et al. (2016) suggested a correlation among the Lyons Group to the Talchir Manendragarh beds and Carrandibby Formation to Umaria and Bap formations of India (Archbold et al. 1996, and references therein), Nilawan Group in Salt Range and the Agglomeratic Slate in Kashmir, Pakistan, eastern Himalaya (Waagen 1881; Reed 1936; Sahni and Srivastava 1956; Dickins 1985; Singh and Archbold 1993) (see Figure 7).

Conclusions

The present contribution is the second report of the palynoflora from the Talchir Formation from the Rajmahal Basin. Based on the first appearance of taxa, two assemblages are described in borehole BRS-2 located in the east-west trending Salbadra-Gomarpahari region between the Brahmani- Birbhum Coalfield. Assemblage I (608.90–599.00 m)- dominated by monosaccates and absence of bisaccates and spores. Assemblage II (592.0–590.80 m)- also dominated by monosaccates, but with the inception of spores, bisaccates and marine palynomorphs (see Table 3). A comparison of our assemblages with the zonation scheme of Tiwari and Tripathi (1992) allowed us to correlate the Assemblage I to the *Potonieisporites neglectus* Assemblage Zone and the Assemblage II to the *Plicatipollenites gondwanensis* Assemblage Zone. However, here we palynologically assigned for the first time a Late Pennsylvanian age to the lowest subsurface interval (590.80–608.20 m) by considering the range of the species of Assemblage I by its correlation with similar palynoassemblages radiometrically constrained to the Late Pennsylvanian across Gondwana, which are devoid of diagnostic Permian pollen grains as well as marine *Eurydesma* fauna and terrestrial glossopterids. They tentatively support an older age (Late Pennsylvanian) at least for the lower interval of the Talchir Formation, until radiometric dates are available. The latter fossils associated to Assemblage II confirm an early Permian age.

Hitherto, an early Permian age was assigned to the *Potonieisporites neglectus* Assemblage Zone of Tiwari and Tripathi (1992) because there has been a tendency to describe each of the lithological subdivisions of the Gondwana sequence separately and describe assemblages that are confined to and based on the litho-stratigraphic subdivision. Therefore the basal most assemblage was confined to Permian. However, in this work we attempted to rectify the conventional concept of confining palynozones to lithological formations and reinforce the significance of considering the ranges of species. As a result it facilitated in the correlation of *Potonieisporites neglectus* Assemblage Zone with similar assemblages from Late Pennsylvanian across Gondwana (Figure 5) for the first time.

A Late Pennsylvanian age for the assemblage is also proposed tentatively on the following basis:

> The absence of Permian marker palynotaxa in the *Potonieisporites neglectus* assemblage zone of Tiwari and Tripathi (1992) (see Table 3).

> The stratigraphic position of its reference section,which corresponds to siltstones above the oldest boulder bed over the Precambrian basement at the Dudhi Nala section, West Bokaro Coalfield (Lele 1975; Tiwari and Tripathi 1992). This position corroborates with the initiation of Gondwana sedimentation in India, which began with the initial relaxation of the Pangean platform near the end of the Carboniferous Period (Veevers and Tewari 1995).

> Its correlation with radiometrically constrained Late Pennsylvanian monosaccate rich assemblages below the *Eurydesma* Fauna and Glossopterids across Gondwana.

> Its older position than the succeeding *Plicatipollenites gondwanensis* Assemblage-Zone, that has been dated as early Permian due to their association with marine *Eurydesma* fauna from Manendragarh beds of Madhya Pradesh State (Lele and Chandra 1972). The oldest occurrence of *Eurydesma* fauna is from the post Ghzelian Hardap shale, which has been radiometrically constrained to the Asselian based on the $^{206}Pb/^{238}U$ age of 297.1 ± 1.8 Ma.

> A Late Pennsylvanian age has been assigned to the Assemblage I of this study since it is correlatable with the *Potonieisporites neglectus* Assemblage-Zone. And an early Permian age has been assigned to the Assemblage II of this study by its correlation with similar assemblage associated with the early Permian marine *Eurydesma* fauna.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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