depth, SOC stock was 85.24, 80.82, 55.84, 62.57 and 51.54 Mg C ha^{-1} under agroforestry system in Thane, Nashik, Chittoor, Tumkur and Bellary respectively. SOC stock in the top 0–30 cm depth was 57.27 Mg C ha^{-1} compared to control (sole crop) with 49.64 Mg C ha^{-1} in Thane (Figure 1). This value is about 1.15 times higher than that of the control. These values are comparable to those in the Mediterranean region (25–50 Mg C ha^{-1})[13,14] and better than 27 Mg ha^{-1} of SOC stock in 0–60 cm layer for agroforestry systems in Central India[15]. In case of Nashik and Chittoor, the SOC stock under agroforestry system was 1.21 times more than the sole cropping in 0–30 cm soil layer. While in Karnataka, it was 1.58 times more in case of Tumkur district and 1.07 times more for Bellary district respectively. In the 0–90 cm soil depth studied, especially the top 0–30 cm contributed almost 67% of the SOC stock in Thane and around 60% in Nashik, 56% in Chittoor and 60% each in Tumkur and Bellary. This might be due to the fact that trees along with herbaceous layer of crops add a lot of organic matter to the soil, which is recognized as an efficient measure to sequester carbon and mitigate climate change. Improved carbon storage of the agroforestry system can also be explained by greater capture of resources such as solar radiation and water combining different components for enhanced biomass that is partly returned to the soil through above- and belowground litter. The agroforestry system existing in the farmer's field not only provides food, fuel, and improves soil health, and helps in water management, but also acts as a major sink for atmospheric CO_2.

1. Smith, K. A., Ball, T., Conen, F., Dobbie, K. E., Massheder, J. and Rey, A., *Eur. J. Soil Sci*., 2003, **54**, 779–791.
2. Verma, K. S., Kumar, S. and Bhardwaj, D. R., *J. Tree Sci*., 2008, **27**(1), 14–27.
3. Jordan, C. F., *Agrofor. Syst*., 2004, **61**, 79–90.
4. Peichl, M., Thevathasan, N. V., Gordon, A. M., Huss, J. and Abohassan, R. A., *Agrofor. Syst*., 2006, **66**, 243–257.
5. Lorenz, K. and Lal, R., *Agron. Sustain. Dev*., 2014, **34**, 443–454.
6. Nair, P. K. R., *Agrofor. Syst*., 2012, **86**, 243–253.
7. Haile, S. G., Nair, V. D. and Nair, P. K. R., *Global Change Biol*., 2010, **16**, 427–438.
8. Upson, M. A. and Burgess, P. J., *Plant Soil*, 2013, **373**, 43–58.
9. Walkley, A. J. and Black, C. A., *Soil Sci*., 1934, **37**, 29–38.
10. Soto-Pinto, L., Anzueto, M., Mendoza, J., Ferrer, G. J. and de Jong, B., *Agrofor. Syst*., 2010, **78**, 39–51.
11. Nair, P. K. R. and Nair, V. D., *Curr. Opin. Environ. Sustain*., 2014, **6**, 22–27.
12. Hendrick, R. L. and Pregitzer, K. S., *J. Ecol*., 1996, **84**, 167–176.
13. Martin, M. P., Wattenbach, M., Smith, P., Meersmans, J., Jolivet, C., Boulonne, L. and Arrouays, D., *Biogeosciences*, 2011, **8**, 1053–1065.
14. Muñoz-Rojas, M., Jordán, A., Zavala, L. M., De la Rosa, D., Abd-Elmabod, S. K. and Anaya-Romero, M., *Solid Earth*, 2012, **3**, 375–386.
15. Swamy, S. L. and Puri, S., *Agrofor. Syst*., 2005, **64**, 181–195.

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RAM NEWAJ
O. P. CHATURVEDI
DHIRAJ KUMAR*
RAJENDRA PRASAD
R. H. RIZVI
BADRE ALAM
A. K. HANDA
S. B. CHAVAN
ANIL KUMAR SINGH
MAYANK CHATURVEDI
P. S. KARMAKAR
ABHISHEK MAURYA
ABHISHEK SAXENA
GARGI GUPTA
KEDARI SINGH

ICAR-Central Agroforestry Research Institute,
Jhansi 284 003, India
**For correspondence.*
e-mail: dhiraj.iari@gmail.com

A new insight into age and environments of intertrappean beds of Mohgaon Kalan, Chhindwara District, Madhya Pradesh using palynology, megaflora, magnetostratigraphy and clay mineralogy

The megaflora-rich intertrappean cherts near the village Mohgaon Kalan in Chhindwara District, Madhya Pradesh (Figure 1 *a*) has been known since 1934 when K. P. Rode[1] first reported dicotyledonous woods from this intertrappean. Sahni and Rode[2] carried out pioneering work on megaflora of this horizon and during the following seven decades numerous additional megafloral remains, representing pteridophytes, gymnosperms, angiosperms, algae and fungi have been reported. However, despite numerous records of megafloral remains from this megafossil Lagerstatten[3,4], the age, whether Maastrichtian or Palaeocene[5] has been difficult to pin down in the absence of unequivocal age marker fossils or any precise radiometric dating.

During the current field investigations for palynological study, multiple intertrappean sediments at different stratigraphic levels within the Deccan volcanic sequence in Chhindwara area have been studied. The previous study[6] has shown that in the Mohgaon Kalan locality there are two intertrappean beds at two stratigraphic levels associated with three flows. The two upper flows (MKF2 and MKF3) are exposed and the lower most flow (MKF1) occurs only as subcrops in the well sections (Figure 1 *b*). The sediments of the lower intertrappean, including the one studied earlier[7–9], occur between MKF1 and MKF2 in the well section. We designate the lower intertrappean as Mohgaon Kalan Well Section (MKWS) and the upper one as Mohgaon Kalan Fossil Forest (MKFF). The present study is aimed to understand the palynofloral composition in the MKWS and MKFF sediments for the

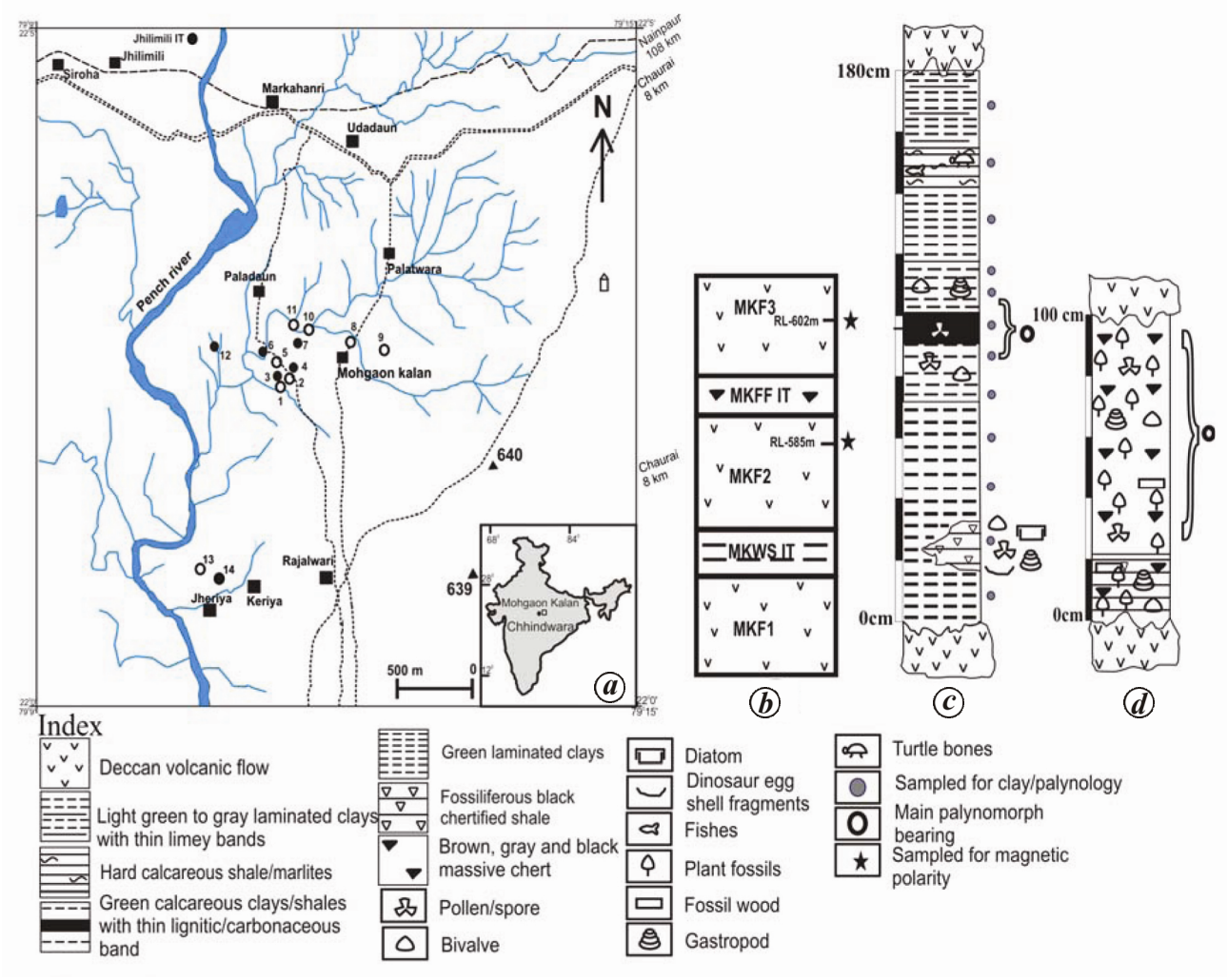

Figure 1. ***a***, Map showing location of sections studied in Mohgaon Kalan locality. 1–9, MKWS well sections and 10–14, MKFF sections/outcrops. (1) Shriwas well, (2) Vishwakarma well, (3) Lodhi well, (4) Jamil well, (5) Hakim well-I, (6) Hakim well-II, (7) Idbibanu well, (8) Government well, (9) Srivastava well, (10) Mohgaon Kalan Nala section-I, (11) Mohgaon Kalan Nala section-II, (12) Mohgaon Kalan Hill section, (13) Jheria-I, (14) Jheria-II. ***b***, Schematic section showing stratigraphic position of MKWS and MKFF intertrappean beds and associated flows MKF1, MKF2 and MKF3 (not to the scale). ***c***, Representative lithosection of MKWS intertrappean as exposed in well sections. ***d***, Lithosection of megaflora bearing MKFF intertrappean. Open and filled circles in Figure 1 *a*, represent sampled and palynomorph productive locations respectively.

age, depositional environments and climatic conditions (Figure 1 *c* and *d*). For stratigraphic constraints palaeomagnetic studies were carried out for the flows MKF2 and MKF3. Clay mineralogy of MKWS sediments was also undertaken for environmental and climatic interpretations. Standard analytical techniques were used for palynological analyses, clay mineralogy and magnetic polarity study. Clay mineral analysis and magnetic polarity studies were carried out at the Department of Geology, University of Delhi and Department of Geology, Pune University respectively.

Several workers sampled Shriwas well (Figure 1 *a*) and reported molluscs, ostracodes and egg shell fragments inferred to be dinosaurian and avian type[7–9]. The recovered palynomorphs were assigned to 22 genera and 26 species and based on palynomorphs such as *Aquilapollenites bengalensis*, *Gabonisporis vigourouxii*, *Ariadnaesporites* and *Triporoletes reticulatus* and diosaurian egg shells, a Maastrichtian age was assigned to the sediment of the well section. During the present study, the MKWS sediments in nine well sections including the previously studied Shriwas well were sampled for palynology and clay mineralogy studies. Of these, only five wells (Figure 1 *a*) yielded good concentrations of palynomorphs assigned to 35 genera and 63 species. Some newly recorded palynomorphs are *Ephedripites* spp., *Scollardia conferta*, *Crenwellia* sp., *Jiangsupollis* spp., *Dipterocarpuspollenites retipilatus*, *Incrotonipollis neyvelli*, *Intratricolpites brevis*, *Psilodiporites erdtmanii* and *Echitricolpites* sp.

The palynoflora from the overlying megaflora-rich black chert of MKFF was first reported by Chitaley[10]. However, she gave only morphological description of some palynomorphs without any taxonomic nomenclature and illustrations. Since then, there have been no further reports of any dispersed palynomorphs from this intertrappean. During the

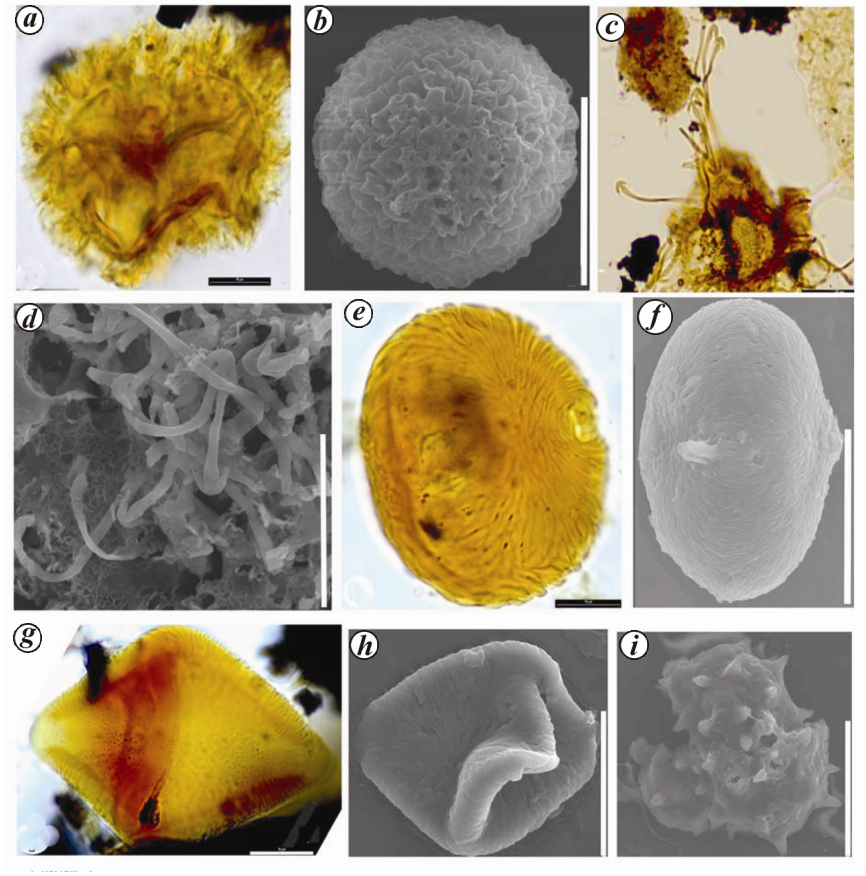

Figure 2 ***a–i.*** Important palynomorphs from Mohgaon Kalan intertrappean sections (scale bar represents 10 µm or otherwise mentioned). ***a***, *Gabonisporis vigourouxii* (slide – MKKP-4, EF-F34); ***b***, SEM photograph of the similar pollen of *Gabonisporis vigourouxii* (scale bar 30 µm); ***c***, *Azolla cretacea* (slide – MKKP-4, EF-R67); ***d***, SEM photograph of the similar pollen of *Azolla cretacea* (scale bar 20 µm); ***e***, *Aquilapollenites bengalensis* (slide – MKGW-2-2, EF-B22/7); ***f***, SEM photograph of the similar pollen of *Aquilapollenites bengalensis* (scale bar 30 µm); ***g***, *Jiangsupollis* sp. A (Slide – MKHW-2-1, EF-V28/4); ***h***, SEM photograph of the similar pollen of *Jiangsupollis* (scale bar 20 µm); ***i***, SEM photograph of *Echitricolpites* sp. A. (scale bar 50 µm).

Table 1. Magnetic polarity data of the flows sampled

Sample no.	PCA (0) dec.	PCA (0) incli.	Polarity
MKF3-A1	284.2	46.9	Reverse/mixed
MKF3-C1	288	46.6	Reverse/mixed
MKF3-E1	267.8	44.4	Reverse
MKF2b-E3	328.2	–22.3	Normal
MKF2-C1	310.9	–39.4	Normal
MKF2a-F1	330.2	–43.8	Normal
MKF2a-H1	312.5	–36.8	Normal
MKF2B-C1	333.1	–25.3	Normal
MKF2b-D1	323.8	–26.5	Normal
JHL-F1a	330	–19	Normal
JHL-F1b	356	–38	Normal
JHL-F2a	136	4	Reverse
JHL-F2b	105	30	Reverse

present study, five geographically separated outcrops of MKFF (Figure 1 *a*) were sampled. Of these, three sections yielded well preserved palyno assemblage with marker Maastrichtian palynotaxa (Figure 1 *a*). The palynoflora from MKFF include 11 genera and 32 species. Some of the important recorded palynotaxa are *Aquilapollenites bengalensis*, *Azolla cretacea*, *Ephedripites* spp., *Farabeipollis* spp., *Gabonisporis vigourouxii*, *Proxapertites operculatus*, *Spinizonocolpites* spp., *Jiangsupollis* spp., *Echitricolpites* sp. A and Normapolles group pollen (Figure 2). Palynoflora from MKWS and MKFF show close similarity, however MKWS has dominance of *Ephedripites* spp., *Spinizonocolpites* spp. and *Proxapertites operculatus* and MKFF has dominance of *Azolla cretacea* and *Gabonisporis vigourouxii*. Qualitatively palynoflora of MKWS is more diverse probably due to better preservation condition.

The sediments of both the MKWS and MKFF at two stratigraphic levels are characterized by the presence of common Maastrichtian marker palynomorph forms such as *Aquilapollenites bengalensis*,

Table 2. Percentage of total clay fractions and fine clay fractions from the Mohagaon Kalan Well Section

	Total clay						Fine clay					
Sample no.	Smectite (%)	Smectite–Chlorite Inter-layering (%)	Chloritized smectite (%)	Illite/mica (%)	Chlorite (%)	Quartz (%)	Smectite (%)	Smectite–Chlorite Inter-layering (%)	Chloritized smectite (%)	Illite/mica (%)	Chlorite (%)	Quartz (%)
1MK	22.28	23.14	–	25.64	6.85	15.42	19.4	33.07	–	32.6	3.08	14.7
2MK	13.63	6.72	–	2.5	13.81	63.63	24.52	51.78	–	12.51	4.9	6.2
3MK	15.8	21.4	19.3	3	9.08	43.2	10.95	29.04	34.04	6.65	5.23	9.04
4MK	38.46	28.3	20.95	1.7	0.79	8.9	22.9	26.32	42.25	1.81	2.72	1.8
5MK	8.07	18.65	4.8	0.28	4.2	61.53	33.65	30.63	10.9	7.5	6.68	4.09
6MK	20.11	22.15	13.86	–	9.09	35.45	18.8	23.39	39.84	3.47	6.48	1.85
7MK	5.17	34.48	40.39	–	3.5	8.37	24.86	30.43	24.74	–	3.04	25.9
8MK	10.43	17.24	–	9.56	20.86	42.02	26.66	10.11	–	8	14.45	26.74
9MK	20	10.41	–	1.24	5.62	63.12	49.1	30.39	–	8.09	5.1	2.37
10MK	47.64	11.76	21.71	–	8.82	3.42	13.84	27.69	–	4.61	15.38	27.69
11MK	11.59	20.86	7.03	1	5.6	53.84	28.58	31.06	18.64	8.28	2.48	8.45

Azolla cretacea and *Gabonisporis vigourouxii, Farabeipollis* spp., *Echitricolpites* sp. and *Jiangsupollis*. The palynotaxa have similarity with Maastrichtian palynomorphs reported previously from other intertrappean localities of Sahyadri Group[11] and Padwar[12] and Ranipur (Campanian to lower Maastrichtian)[13].

Magnetic polarity analysis indicates normal polarity chron for flow MKF2 which stratigraphically separate MKWS and MKFF and mixed to reverse polarity signatures for MKF3 (Table 1) capping the MKFF. Thus, it is interpreted that the deposits of MKWS and flow MKF2 represent C30N whereas the MKFF sediments are Maastrichtian and capping MKF3 flow is of mixed to reverse polarity. Presently due to lack of any radiometric data it is difficult to interpret if MKF3 erupted during C29 R Maastrichtian or Danian. In the adjoining locality at Jhilimili (~5 km NW of Mohagaon Kalan) the P1a foraminifera bearing intertrappean Danian sediments[14] are present. The study of the lower flow (JHL-F1) below Jhilimili sediments and the capping upper flow (JHL-F2) indicate C30N and Danian C29R respectively (Table 1). Thus, both in MKFF and Jhilimili the lower most transition from C30N to C29R is recorded.

Based on megaflora a wide range of depositional environments from freshwater to estuarine and even marine was suggested[3,4]. Prevalence of freshwater depositional environments is indicated by the presence of algae, *Spirogyra* and *Oedogonium*, and the water ferns *Azolla*, *Salvinia* and *Marsilea*, whereas estuarine conditions are indicated by *Nypa*, *Barringtonia* and *Cocos*. In addition to megaflora, the palynoflora also shows presence of both freshwater taxa such as *Azolla (Azolla cretacea*) and estuarine palynomorphs such as *Spinizonocolpites echinatus* and *Proxapertites operculatus.* The pollen grains of *Spinizonocolpites echinatus* show affinity with the extant mangrove palm *Nypa fruticans* and *Proxapertites operculatus* is believed to be an extinct monocot herb having affinity with Araceae that live in coastal environments along the shores of river channels and lagoons[15]. Significantly, fossils of *Nypa* in MKFF are also represented by root[16] and fruit[17] including the oldest record of *Nypa* fruit from this area by Sahni and Rode[2]. Climatic reconstruction based on megafloral remains of the intertrappean beds was first attempted by Bande and Prakash[18]. Among the recorded megafossil remains of plants which are important climatic indicators are *Anacardioxylon semecarpoides* (Anacardiaceae), *Polyalthioxylon parapaniensis* (Annonaceae), *Sterculioxylon shahpurensis* (Malvaceae), *Musa cardiosperma* (Zingiberaceae) and *Phoenix robusta* and palm fossils that suggest prevailing subhumid to humid climatic conditions during MKFF[19]. The presence of high concentrations of fungal spores and fruiting bodies of epiphyllous fungi in the sediments of MKWS and MKFF also indicates prevalence of humid tropical climate[20].

In addition to megaflora clay minerals are also good climate proxies[21]. For the current study 11 clay samples were drawn from different MKWS well sections for total clay (<2 μm) and fine clay (<0.2 μm). The clay mineralogy indicated presence of two types of chlorite-trioctahedral and regularly interstratified, mixed layer smectite/chlorite. Illite/mica shows two peaks implying the presence of both biotite and muscovite. Quartz shows a peak at ~3.3 Å. Smectite is the first weathering product of Deccan basalt and it is nearer to montmorillonite in the montmorillonite–nontronite series[22]. Dominance of smectite indicates deposition under arid–semiarid conditions whereas formation of smectite/chlorite suggests a transition from arid to humid climate (Table 2). In a humid tropical climate smectite is ephemeral and likely to be chloritized[22]. Hence, clay mineralogy of MKWS indicates fluctuating humid to semiarid conditions. Significantly pyrite grains have been recorded from the black carbonaceous shales of MKWS which also suggest prevalence of anerobic humid climatic conditions.

Based on our study it is concluded that (1) In the Mohgaon Kalan locality the intertrappean beds (MKWS and MKFF) at two stratigraphic levels are characterized by marker Maastrichtian palynomorphs. The lower intertrappean, MKWS is encountered in a series of dug wells whereas the upper MKFF is exposed on the surface. (2) Magnetic polarity study indicates normal polarity for flow MKF2 separating MKWS and MKFF and mixed to reverse polarity for MKF3 capping MKFF. The flow MKF2 is interpreted to be of C30N Maastrichtian and MKF3 can

either be of C30N or C29R Maastrichtian–Danian. (3) Palynomorphs, megafossils and clay mineralogy of the sediments indicate deposition of both MKWS and MKFF sediments in freshwater to estuarine environments under humid–sub humid to semiarid climatic conditions.

1. Rode, K. P., In Conference Proceedings 21st Indian Science Congress Bombay, 1934, p. 350.
2. Sahni, B. and Rode, K. P., *Pro. Natl. Acad. Sci. India*, 1938, **7**, 165–174.
3. Kapgate, D. K., *Gond. Geol. Mag.*, 2005, **20**(1), 31–45.
4. Bonde, S. D., *Palaeobotanist*, 2008, **57**, 141–164.
5. Lakhanpal, N. R., *Taxon*, 1970, **19**(5), 675–694.
6. Samant, B., Mohabey, D. M. and Kapgate, D. K., *J. Geol. Soc. India*, 2008, **71**, 851–858.
7. Srinivasan, S., In *Cretaceous Stratigraphy and Environment* (ed. Sahni, A.), *Rama Rao volume, Mem. Geol. Soc. India*, 1996, **37**, 321–336.
8. Kar, R. K. and Srinivasan, S., *Geophytology*, 1997, **27**, 17–22.
9. Kumaran, K. P. N., Bonde, S. D. and Kanitkar, M. D., *Curr. Sci.*, 1997, **72**, 590–592.
10. Chitaley, S. D., *J. Indian. Bot. Soc.*, 1950, **29**, 30–34.
11. Samant, B. and Mohabey, D. M., *Geol. Soc. Am. Spl. Publ.*, 2014, **505**, 171–191.
12. Mathur, N. S. and Sharma, S. D., In A Seminar cum Workshop IGCP 216 and 245 (eds Sahni, A. and Jolley, A.), 1990, pp. 58–59.
13. Prakash, T., Singh, R. Y. and Sahni, A., In A Seminar-cum-Workshop IGCP 216 and 245 (eds Sahni, A. and Jolley, A.), 1990, pp. 68–69.
14. Keller, G. *et al.*, *Earth Planet. Sci. Lett.*, 2009, **282**, 10–23.
15. Zetter, R., Hesse, M. and Frosch-Radivo, A., *Rev. Palaeobot. Palynol.*, 2001, **117**(4), 267–279.
16. Verma, C. L., *Curr. Sci.*, 1979, **43**, 289–290.
17. Chitley, S. D. and Namburdiri, E. M. V., Symposium on Global Environment and Diversification of Plants through Geological Time (ed. Pant, D. D.), Birbal Sahni Centenary Volume, Allahabad, 1995, pp. 235–248.
18. Bande, M. B. and Prakash, U., *Geophytology*, 1982, **12**, 152–165.
19. Smith, S. Y. *et al.*, *Paleontol. Soc. Papers*, 2015, **21**, 137–166.
20. Selkirk, D. R., *Proc. Linn. Soc.*, 1975, pp. 70–94.
21. Chamley, H., *Clay Sedimentology*, Springer Verlag, Heidelberg, 1989, p. 623.
22. Herbillon, A. J., Frankart, R. and Vielvoye, L., *Clay Minerals*, 1981, **16**, 195–201.

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DEEPALI THAKRE[1]
BANDANA SAMANT[1,*]
D. M. MOHABEY[1]
SATISH SANGODE[2]
PANKAJ SRIVASTAVA[3]
D. K. KAPGATE[4]
RASIKA MAHAJAN[2]
NEHA UPRETI[3]
STEVEN R. MANCHESTER[5]

[1]*Department of Geology, Rashtrasant Tukadoji Maharaj Nagpur University, Nagpur 440 001, India*
[2]*Department of Geology, Savitribai Phule Pune University, Pune 411 007, India*
[3]*Department of Geology, University of Delhi, Delhi 110 007, India*
[4]*Department of Botany, J.M. Patel College, Bhandara 441 904, India*
[5]*Florida Museum of Natural History, Gainesville, Florida, USA*
**For correspondence.*
e-mail: bandanabhu@gmail.com