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Evidence of wildfire based on microscopic charcoal, spores and pollen grains from Early Cretaceous sediments of South Rewa and Kachchh basins, India

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ABSTRACT

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Early Cretaceous sedimentary successions in South Rewa and Kachchh basins of India comprising well–preserved macro–and microscopic biota, are considered to be significant late Gondwanan Lagerstätte of this epoch. Several sedimentary successions of the Bansa Formation in South Rewa and Bhuj Formation in Kachchh basins also contain abundant charcoalified plant fragments and thermally altered spores and pollen grains, indicating effect of fire on the vegetation during the deposition of sediments. Light and scanning electron microscopic images of the fire affected plant remains exhibiting less to severe morphologic distortions, *viz*. rupturing, shrinkage, curling and perforations due to stress and weight loss. The changes observed in their colour from pale yellow to brown, dark brown and black are most conspicuous and primarily related to the high temperature effect before their burial in the sediments. Botanical affinity of these thermally altered and unaltered spores, pollen grains, charcoalified and non–charcoalified woody fragments indicates their derivation from the vegetation constituted mainly by Pinales, Cycadales, Bennettitales, Ginkgoales, tree ferns and other herbaceous pteridophytes. Record of the charcoalified plant fossils from various sedimentary successions of both the basins provides evidence of the wildfire phenomenon during the Late Gondwanic regimes in India.

Key–words—Palynoflora, Microscopic charcoal, Wildfire, Bansa and Bhuj formations, Early Cretaceous, India.

भारत वर्ष के दक्षिण रीवा एवं कच्छ द्रोणियों के प्रारंभिक क्रिटेशस अवसादों से प्राप्त सूक्ष्मदर्शीय काष्ठ कोयला, बीजाणु एवं पराग कणों पर आधारित वन अग्नि का प्रमाण

माधव कुमार

सारांश

भारत वर्ष के दक्षिण रीवा एवं कच्छ द्रोणियों के प्रारंभिक क्रिटेशस की क्रमवत उत्तराधिकार शैलों में पाए जाने वाले संपरिरक्षित स्थूल और सूक्ष्मदर्शीय जीवजात विलंबित गोंडवाना के महत्वपूर्ण जीवाश्म माने जाते हैं। दक्षिण रीवा में बांसा तथा कच्छ द्रोणियों में भुज शैलसमूह में पाए जाने वाले खंडित काष्ठ कोयलायुक्त एवं वर्धित ऊष्मा के प्रभाव से परिवर्तित बीजाणु एवं पराग कण की परिवर्तित संरचनाएं इन अवसादों के निक्षेपण के समय विद्यमान वनस्पतियों पर अग्नि के प्रभाव को इंगित करती हैं। इन अग्नि तथा इससे उत्पन्न वर्धित ऊष्मा द्वारा प्रभावित पादप का सामान्य एवं क्रमवीक्षण इलेक्ट्रॉन सूक्ष्मदर्शियों द्वारा अवलोकित प्रतिकृतियों की संरचनाओं की आकृति में परिवर्तन उनमें व्याकर्षण के उपरान्त विदीर्णन, संकुचन, कुंचन एवं निच्छिद्रण उनमें प्रत्याबल एवं भार ह्रास के कारण हुई है। इसके साथ ही हल्के पीले से भूरे, गहरे–भूरे तथा काले रंगो में उनके अतिविशिष्ट तथा अवसादों में संरक्षित होने के पूर्व इन पर अत्यधिक ऊष्मा के प्रभाव को इंगित करते हैं। इन अत्यधिक ऊष्मा से भावित तथा अभावित बीजाणुओं, पराग कणों, सूक्ष्म काष्ठ कोयलाकृत तथा गैर–काष्ठ कोयलाकृत एवं खंडित संरचनाओं की वानस्पतिक सजातीयता पाइनेल्स, साइकेडेल्स, बेन्नेटिटेल्स, जींगोयेल्स, वृक्षीय पर्णांग तथा अन्य शाकीय टेरिडोफाइट्स पादप समूह से व्युत्पत्ति को दर्शाते हैं। दोनों द्रोणियों के विविध अवसादी अनुक्रमों से प्राप्त सूक्ष्म काष्ठ कोयलाकृत पादप जीवाश्म के अभिलेख भारत में विलंबित गोंडवाना की प्रवृत्तियों एवं घटनाक्रम में वन अग्नि के प्रमाण प्रदान करते हैं।

सूचक शब्द—परागाणुवनस्पति–जात, सूक्ष्मदर्शीय काष्ठ कोयला, वन अग्नि, बांसा व भुज शैलसमूह, प्रारंभिक क्रिटेशस, भारत।

INTRODUCTION

FOSSIL charcoal, the main product of wildfire documented in the Phanerozoic sedimentary deposits has much value in understanding the impact of wildfire during geologic ages (Scott, 2000, 2010; Scott *et al*., 2000). These are the incompletely combusted tissues generated from various plant organs during pyrolysis under oxygen–depleted conditions and preserved in sediments without major morphological changes (Scott, 2010). Sometimes they degrade very slowly compared to the non–charcoalified plant remains during their burial in host sediments (Ascough *et al*., 2011; Glasspool *et al*., 2015). Charcoals (macro–and microscopic) are recorded in sedimentary deposits from Silurian (440 million years)

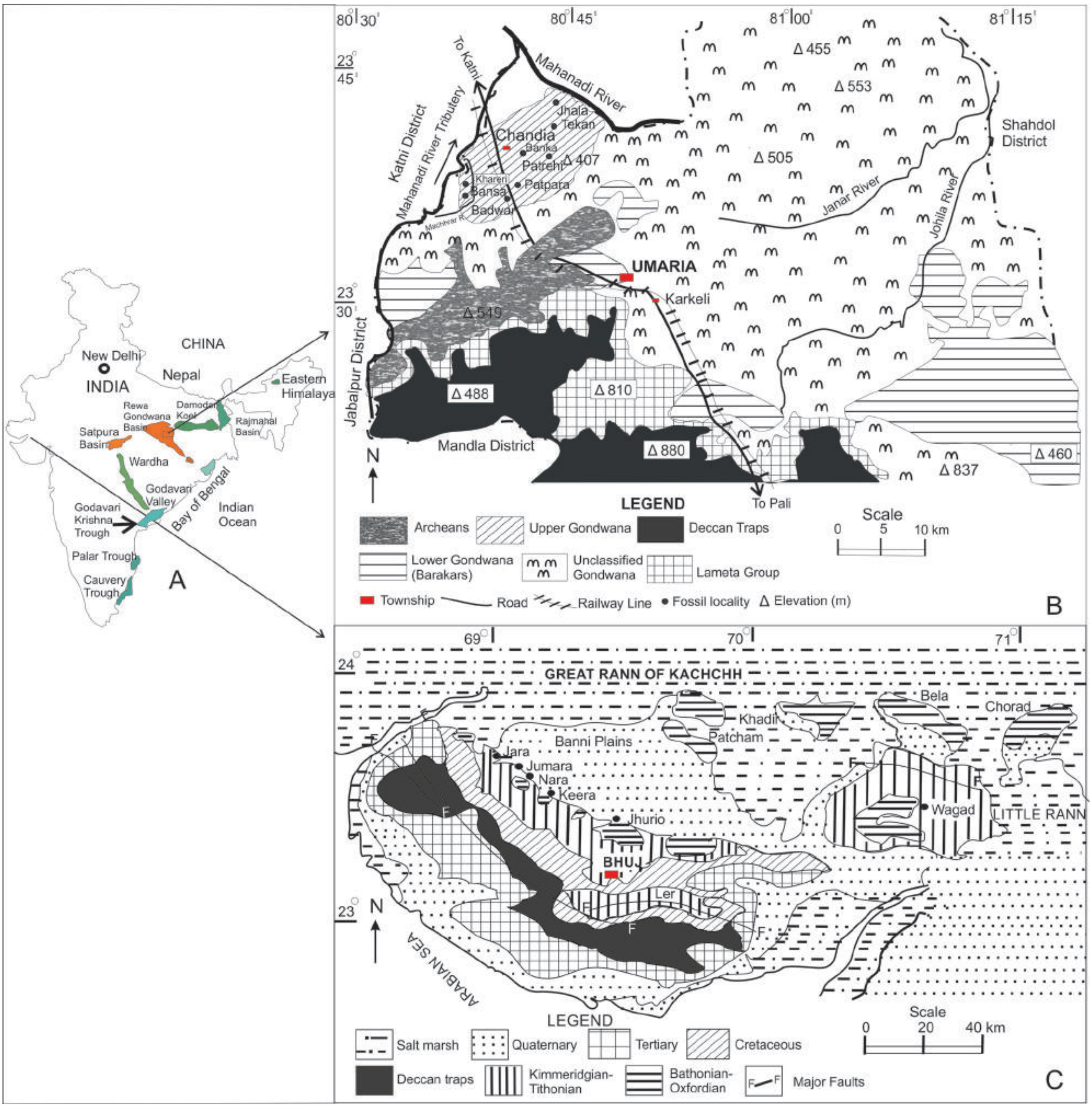

Fig. 1—A. Geographic location of Gondwanic basins in India including South Rewa and Kachchh basins; B. Geological map of South Rewa Basin in north of Umaria District, Madhya Pradesh (partially modified after Central Ground Water Board, North Central Region Report, 2013 and C. Geological map showing location of the study area in Kachchh (partially modified after Fürsich *et al*., 1991).

to Holocene (0.01 my) and in ancient archaeological sites (Glasspool *et al*., 2004; Scott & Damblon, 2010). The phenomenon of wildfire was common in Permian and more frequent during late Jurassic to Cretaceous in both the hemispheres (Belcher & McElwain, 2008; Belcher *et al*., 2010; Brown *et al*., 2012). Based on the published records and current knowledge 'Cretaceous' is considered as particular 'high–fire' period in the earth's history (Bond & Scott, 2010; Brown *et al*., 2012).

Earlier studies for reconstructing local, regional or global fire events were based on the larger pieces of charcoals (Scott, 2000). Now–a–days use of microscopic charcoal in palynological slides or in thin slide preparations for predicting such events is common (Clark, 1988; Whitlock & Millspaugh, 1996; Scott, 2000). In spite of the megascopic charcoal formed from vegetative organs (leaf, stem and root) of plants, a large number of microscopic fragments were also derived from both vegetative and reproductive organs (sporophylls)/organelles (spores and pollen grains). Spores and pollen grains which were liberated or residing in spore/pollen sacs display moderate to severe changes in morphology and colour due to the effect of the high temperature on them. Present study is based on the analysis of microscopic charcoal and thermally altered spores and pollen grains recorded from the Early Cretaceous sedimentary successions of South Rewa and Kachchh basins, and provide an evidence of the late Gondwanan wildfire in India.

Early Cretaceous sedimentary successions of South Rewa and Kachchh basins comprise floral assemblages of various plant groups, viz. Pinales, Bennettitales, Cycadales and pteridophytes (Bose & Sukh–Dev, 1960; Maheshwari, 1974; Bose & Banerjee, 1984; Banerjee *et al*., 1984). Several faunal remains have also been recorded by Krishna (1997) and Desai and Saklani (2015). These basins host typical charcoal bearing Early Cretaceous horizons occurring in a wide region and embody unique fire affected plant morphologies of the common plant groups. These plant groups are very significant in establishing relationships between the host sediments, and the similar fire events which destroyed the existing vegetation of a wide geographic region of the Indian peninsula. Study on such fire affected plant remains reveals (i) morphological changes in spores, pollen grains and pieces of leaf and woody fragments due to the effect of high temperature, (ii) fire and vegetation interaction and burial of abundant microscopic charcoal in various lithotypes found at distant places, and (iii) types of vegetation destroyed by the fire.

GEOLOGICAL SETTINGS

South Rewa Basin

South Rewa Basin comprises lower and upper Gondwana sediments deposited in the Narmada Graben of central India. The graben contains vast early Gondwana (Permian) coalfields at Umaria and Korar (Raja Rao, 1983) are mined since one and half–century. The Late Gondwana (Jurassic–Early Cretaceous) thin coal seams, carbonaceous shales, mudstones, clays, sandstones, etc. occur at several places. The late Palaeozoic–Mesozoic sediments circumscribed within the lower and upper Gondwana Super Groups are overlying Lameta Formation of the post–Gondwana (Late Cretaceous). The Gondwana coalfields are arbitrarily designated here as Supra Barakar, which includes Barakar (Lower Permian), Tiki/Pali (Late Permian to Carnian) and Parsora (Late Norian to Rhaetic). The Chandia bed is considered to be younger in age (Aptian–Albian) known as Bansa Formation. This formation is about 70 m thick and occurs un–evenly at various places around Chandia Town in northern part of the basin. Magmatic rocks and ash beds, sparsely distributed around Patrehi and Banka villages (Fig. 1A) are situated 2–4.5 km away from the charcoal bearing horizons. A major part of these basic rocks has been removed from many places by the denudation, erosion, mining activities and road constructions. Other Gondwanic sediments occur towards the southwestern side of the basin and encompass Precambrian rocks at the base and overlying Lameta Formation and Deccan Traps at the top. Late Triassic and middle–late Jurassic beds occur at some places in the northeastern part of the Umaria District (Kumar & Ram–Awatar, 2010). The Lameta and Deccan traps are absent around Chandia, while Bansa Formation occupying a vast area in between the Umrar and Mahanadi rivers, comprises less diversified *Ptilophyllum* and other late Gondwanan flora (Bose & Sukh–Dev, 1960; Maheshwari, 1974). Some complete and fragmented leaf remains recorded from mudstones and carbonaceous shales, occur at various localities, viz. Khareri, Badwar, Patparha and Tekan, etc. The regional topography of the basin is hillocky at the elevation of about 400–550 m above the mean sea level and sparsely blanketed by alluviums and vegetation.

Kachchh Basin

Kachchh Basin covers a vast land area about 43,000 square km in the Gujarat State of western India. Its western border is extended to the Pakistan and Arabian Sea and eastern to the Rajasthan. Bhuj Formation of the basin comprises youngest Gondwanic deposits, hosting paralic and non–marine sedimentary succession (Biswas, 1977, 1980, 1982). The main physiographic feature of the basin displays hills, hillocks and plains, encompassing salt flats in a wide region known as (i) great Rann, (ii) little Rann in the east, (iii) Banni planes (grasslands) in the central region, and (iv) coastal plains along the Arabian Sea (Sorkhabi, 2014) towards the south (Fig. 1B). During middle and upper Gondwanic regimes, the basin received sediments from the westerly deepening epi–continental sea because of the extension of Tethys, in which a thick pile of sediments ranging in age from the Middle Jurassic to the Early Cretaceous were deposited under shallow

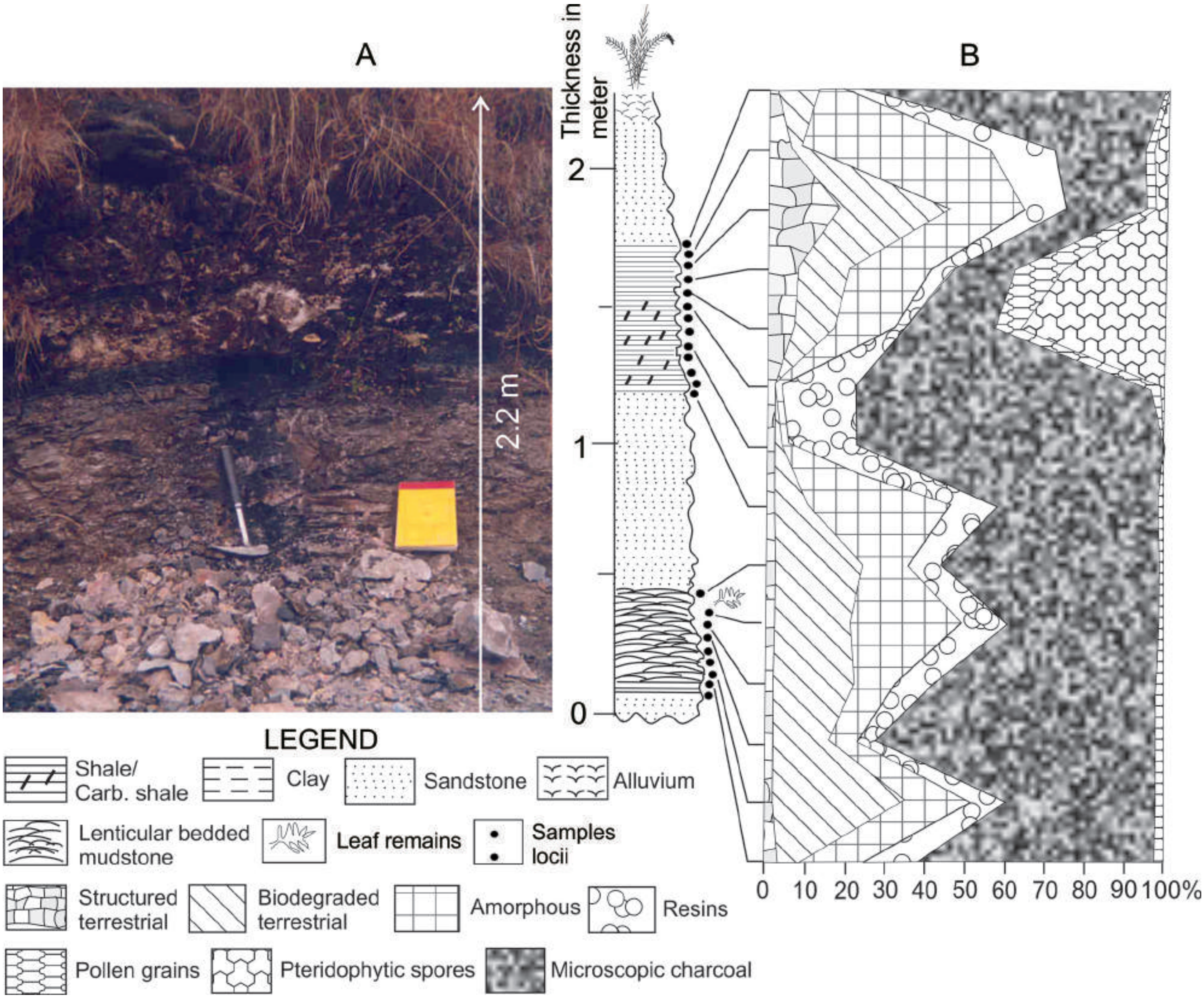

Fig. 2—Showing charcoal bearing section exposed at Khareri in the South Rewa Basin, with lithology and relative abundances of sedimentary organic matter; A. Image of the exposed section; B. Abundance of microscopic charcoals, spores/pollen grains and other sedimentary organic matter in various samples collected from the section.

marine to deltaic environments (Babu, 2006). The western margin of the basin was developed by the consequences of the depositional activities in early syn–and post–rifting phases, where a series of local and regional horsts and grabens came into existence and gave rise to unique geological settings on the land and offshore regions (Biswas, 1982). The grabens in the basin were filled with 2500 m Mesozoic and about 550 m thick Cenozoic organic rich sediments on land, and up to 4500 m thick Tertiary sediments in offshore regions. Mesozoic sediments of the basin is mainly comprising rift fill of the late Triassic continental, fluvio–deltaic of the middle to late Jurassic transgressive and late Jurassic to early Cretaceous regressive phases (Biswas, 1987, 1999, 2002). The basal Precambrian rocks over which Mesozoic sediments lie are not exposed in the Kachchh Basin (Karanth & Gadhavi, 2007). Intrusive bodies of igneous rocks that include coarse to fine grained melanocratic alkaline basic rocks to oversaturated leucocratic granophyres occurring at various places, are intruded in Mesozoic sediments at many places in the basin (Das & Guha, 2000; Karmalkar *et al*., 2005).

MATERIAL AND METHODS

Eighty nine samples collected for palynological analyses from various measured stratigraphic successions in both the basins are given in lithologs of Figs 2–7. The technique proposed by Brown (1960) and Batten & Morrison (1983) was used for the extraction of palynomorphs, charcoalified remains and other organic particles. About 50 grams of pea–sized broken sediment samples were treated with 25–30%

dilute hydrochloric acid, 30–40 ml of 30% hydrofluoric acid and 30% dilute nitric acid following the standard maceration techniques. The acid–free digested materials were treated further with 3–4 % potassium hydroxide solution for two–three minutes and washed by water through 500–mesh strainer and liberated residues were collected in glass beakers. One drop of concentrated residue containing palynomorphs was mixed with polyvinyl alcohol solution and smeared on glass cover slips (size 22 x 44 x 0.13 mm). The cover slips were dried at the room temperature. The dried cover slips were mounted on the glass slides with Canada balsam and dried in the oven at 70ºC for 3–4 days. The detail morphology of charcoalified remains were observed under high power light and LEO 430 scanning electron microscopes. Relative abundances of charcoalified plant remains and palynofossils were determined by the counting of about 300–500 specimens in each slides. Slides of palynomorphs used in Pls 1–3 and 5 are housed in the repository of the Birbal Sahni Institute of Palaeosciences, Lucknow for further reference.

RESULTS

Slides of the productive samples from four sedimentary successions of the Bansa Formation in South Rewa and Bhuj Formation of Kachchh basins were examined by using light and scanning electron microscopes. Details of the samples, characteristics of microscopic charcoal, thermally altered spores and pollen grains, well–preserved cellular structure with their abundances analysed from samples of each lithotypes are explained below–

Effect of high temperature on plant organs/organelles and morphology of charcoalified remains

Burning of various plant organs by the direct contact of fire flames generated charcoals due to charring barks of the stem including its branches and vascular tissues, viz. xylem, phloem, cambium, parenchymatous tissues, rays, tracheids and pits of the stem and woods. A majority of broken foliages and their tissues containing leaf cuticles, stoma and guard cells of the young or matured leaves, leaf needles and sporophylls are discernible (Pls 4–5). Plants or their organs which were lying beneath the heating nooks of forest fire were also affected by the high temperature. The plant organs were dried due to tissue/cell necrosis and wilted because of acute volatilization of protoplasmic fluids. Earlier experiments have shown effect of the various degrees of high temperature on plant organs and considerable changes have been noticed in their morphology. Such effects brought out structural changes in organs and their organelles finally forced for their charcoalification (Widsten *et al*., 2002; Edwards & Axe, 2004; McParland *et al*., 2007; Hudspith & Belcher, 2017). Rosenberg *et al*. (1971) opined that the rise of air temperature above 60ºC is sufficient to kill stem shoots by accelerating protein denaturation during heat–induced necrosis in it. The decrease in the size of woody tissues affected by the high temperature at ~120ºC was noticed by Korkut *et al*. (2008), who observed that release of some light volatile materials caused a significant loss in their weight. The heating treatment above 160ºC brought out plastification on the solid wood surfaces by transforming lignin to thermoplastic condition, resulting densifying and compactness in the solid wood surface (Follrich *et al*., 2006). Temperature variation between 171–196ºC, causes defibration on the chemical properties of hard woods (Widsten *et al*., 2002). The rise of temperature between 220–230ºC causes fusion in cell walls (Jones & Chaloner, 1991), while its increase between 350–400ºC severely affects plant tissue system of various organs due to the homogenization of cell walls (Hudspith & Belcher, 2017). The effect of heating through variable high temperature caused changes in the colour of plant organs from pale yellow to brown, dark brown or black (Umbanhower & Mcgrath, 1998). McParland *et al*. (2007) observed that woody parts of the tree ferns exposed to the ambient temperature >270º C, a noticeable breakdown occurs in their cellulose and lignins. They also proved that plant tissues affected by the rising of temperature >500ºC became fragile, because of the acute pyrolysis of cellulose, hemicellulose and lignins. Phytoclasts affected by the intense heat before their burials became completely opaque or dark brown with angular outlines as shown in Pl. 5, figs 4–18. Morphological changes occurring in pollen grains through various degrees of heating temperature were observed by Kedves & Kincsek (1989), Kedves *et al*. (2000) and Ujiié *et al*. (2003). These authors have observed that temperature between 150–200ºC, causes weight loss, amalgamation and rupturing in exinal features and reduction or enlargement in size and shapes of the pollen grains. A noticeable distortion in shape and darkening in colour observed in *Pinus thunbergii* pollen grains treated between 159–290ºC by Ujiié *et al*. (2003) is significant.

The other reason for darkening of the structured phytoclasts is slow oxidation during their initial phases of burial, which may be distinguished by their detailed morphological observations. Such phytoclasts oxidized by the available oxygen in sedimentary matrices may possess microbial degradation (Demaison & Moore, 1980; Nealson, 1997). Plant remains which were buried in sediments and later affected by the high temperature due to the intrusion of magma or situation of host sediments within the shear zone (Gray & Boucot, 1975) do not show acute angularity or shrinking in their shape and size. In such conditions, a majority of fossilized plant remains uniformly turned yellow to brown and black, depending on variability in heating of the affected host rocks. The morphological changes observed in the fire affected fossilized plant pieces obtained from various lithotypes of the studied sedimentary successions are explained below.

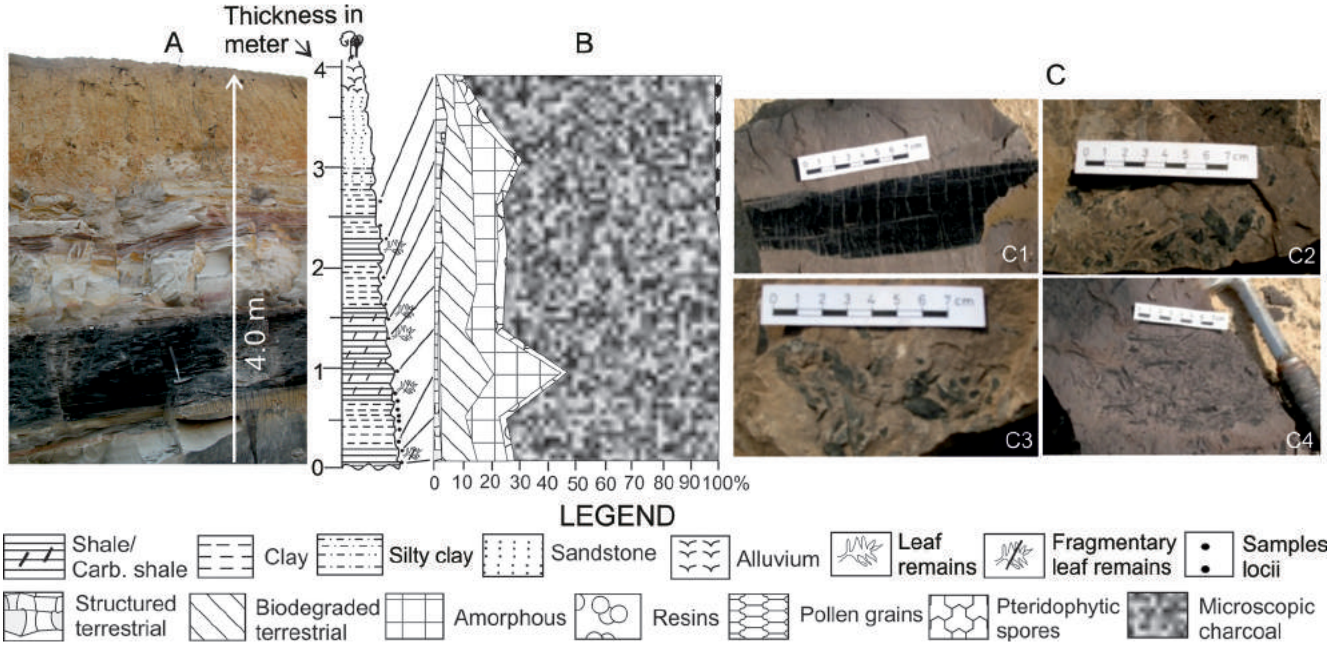

Fig. 3—Showing image of the charcoal bearing section exposed in mining area at Badwar in the South Rewa Basin, lithology and relative abundance of sedimentary organic matter; A. Image of the exposed section; B. Abundance of microscopic charcoals, spores/pollen grains and other sedimentary organic matter in various samples collected from the mine pit section; C. Charcoalified plant mega–remains obtained from the section; C1. A charcoalified piece of wood (fire scars are visible); C2–C3. Charcoalified pieces of leaves, scales and conifer seeds; C4. Thermally altered plant remains.

Leaves and pre–foliated shoots

Thermally affected young and matured (including microphylls) leaves, pre–foliated shoots, leaves or young crozier of ferns (Pl. 5.1–2) exhibit alterations in their morphological features due to necrosis in their tissues, induced by the various degrees of high temperature. High temperature also caused adverse effects on their physiological activities (Michaletz & Johnson, 2007). Morphological change occurs in the single layer epidermal tissues and parenchymatous cells (Pl. 5.3, 5). Coalescence of epidermal cells and rupturing in cellular organizations (Pl. 4.6, 8, 9), shrinkage and distortion of stomatal apparatus (Pl. 5.3) and sometimes curling of needle–shaped leaves are observed because of stress in their epidermis and vascular tissues (Pl. 5.14) due to volatilization of protoplasmic fluids. The opening of stomatal pores, constriction in size of the guard and accessory cells are also visible (Pl. 5.3, 9) in fire–affected leaf tissues.

Stems and barks

External and internal barks of the young trees or their branches are more sensitive to the fire than the older ones (Frejaville *et al*., 2013). Stems of old trees bearing with fissured barks were primarily faced various degrees of high temperature during onset of the fire (Michaletz & Johnson, 2007). The radiation of heat during fire favoured rapid volatilization of protoplasmic fluids, thermal degradation of living tissues and mortality of the periderm, cortex, phloem, xylem, cambium and other vascular tissues (Frejaville *et al*., 2013). A majority of these tissues turned into highly fragile charcoals, which were disintegrated into smaller

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PLATE 1

(Scale bar = 30 µm) →

1. *Cyathidites australis* Couper, Slide No. 14444 P14.
2. *Dictyophyllidites crenatus* Dettmann, Slide No. 14447 P14.
3. *Biretisporites* sp., slide no. BSIP 14437 E29, Slide No. 14444 P14.
4. *Gleicheniidites senonicus* Skarby, Slide No. 14448 Q37.
5. *Laevigatosporites ovatus* Wilson & Webster, Slide No. 14437 H39.

6–7. *Lycopodiumsporites ambefoliolatus* Brenner, Slide No. 14436 P51, 14437 K20.

8. *Retitriletes tennuis* Backhouse, Slide No. 14453 K32.

9, 12. *Foveosporites* sp., Slide No. 14444 P13, 14439 K48.

10. *Streisporites viriosus* Dettmann & Playford, Slide No. 14453, O25.
11. *Sestrosporites* sp., Slide No. 14453 O43.
13. *Couperisporites complexus* (Couper) Pocock, Slide No. 14449 Q21.
14. *Ruffordia australiensis* Dettman & Clifford, 1992 Slide No. 14438 R27.
15. *Contignisporites glebulentus* Dettmann, Slide No. 14437 G29.
16. *Neoraistrikia* sp., Slide No. 14438 Q27.
17. unidentified spore, Slide No. 14438.

18–19. *Cycadopites grandis* De Jercy & Hamilton, Slide No. 14436 J27, 14447 N50.

20–21. *Araucariacites australis* Cookson, Slide No. 14435 O30, 14437 J39.

PLATE 1

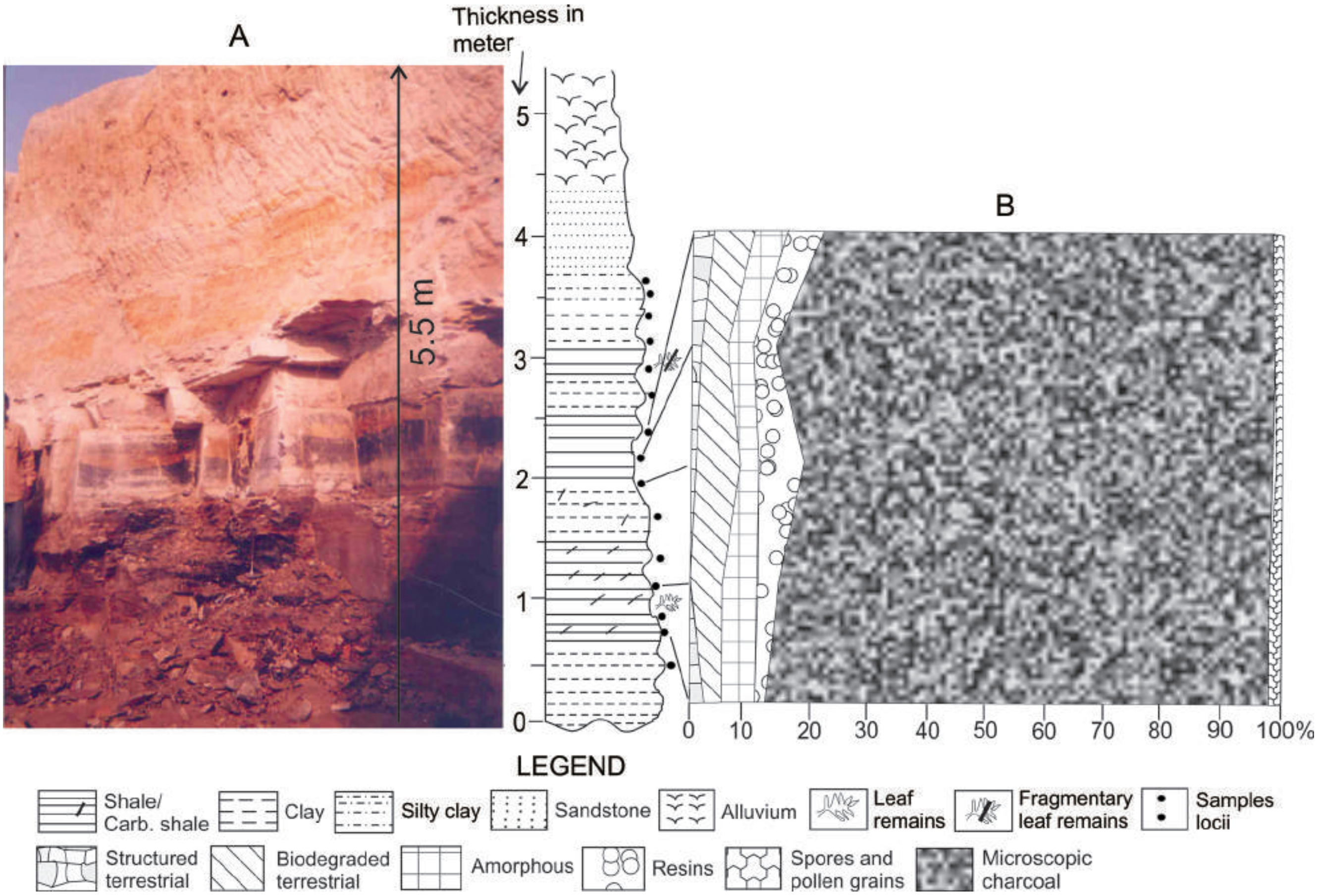

Fig. 4—Photograph showing charcoal bearing section exposed in mining area at Patparha in the South Rewa Basin, lithology and frequency of sedimentary organic matter; A. Image of the exposed section; B. Abundances of microscopic charcoals, spores/pollen grains and other sedimentary organic matter in various samples collected from the section.

pieces during transportation and burial in the host sediments. Many charcoalified woody pieces obtained from sediments of all studied stratigraphic successions exhibit manoxylic/pycnoxylic anatomical details (Pl. 4, 5). These woody pieces appeared in flat and fracturing blocky shapes or in forms of cubes or cuboids (Pl. 4.1, 3, 7, 10). Such charcoalified forms show distortions in internal morphological features, but their histological features are visible in uniseriate, biseriate or multiseriate pits of the tracheids, (Pl. 4.1–12; Pl. 5.6–7, 10–12). Under acute alteration stages perforations in the vessels and wood parenchyma are very common (Pl. 4.3, 15; Pl. 5.12, 15–18). The homogenized cell walls of vascular tissues and transformation of stored foods or protoplasmic fluids, sometimes turned into carbon spherules are also visible (Pl. 4.11–12; Pl. 5.16–18). Cracking in stems and twigs is common during pyrolysis of woody organs. Sometimes impressions of fire scars are visible on charcoalified fossil stems (Fig. 3 C1).

PLATE 2

(Scale bar = 30 µm)

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1. *Callialasporites trilobatus* (Balme) Sukh–Dev, Slide No. 14455 M24.
2–3. *Callialasporites discoidalis* (Döring) Bhardwaj & Kumar, Slide No. 14441 E14, 14436 W40.
4. *Callialasporites* sp. A, Slide No. 14454 X16.
5–6. *Callialasporites dampieri* (Balme) Sukh–Dev, Slide No. 14437 F39, R38.
7. *Callialasporites minutus* (Tralau) Guy, Slide No. 14437 J43.
8. *Callialasporites* sp. B, Slide No. 14441 P43.
9. *Tsugaepollenites dampieri* (Balme) Dettmann, Slide No. 14437 G30.
10. *Falcisporites stabilis* Balme, Slide No. 14481 U22.
11. *Podocarpidites herbstii* Berger, 1446.
12. *Alisporites thomasii* (Couper) Venkatachala *et al.*, Slide No. 14442 U42.
13. *Alisporites* sp., Slide No. 14453 S34.
14. *Podocarpidites ellipticus* Cookson, Slide No. 14442 O11.
15–16. *Platysaccus densus* (Venkatachala) Kumar, Slide No. 14443 M21, 14437 K42.
17. *Parasaccites* sp. slide no. 14451 X19.

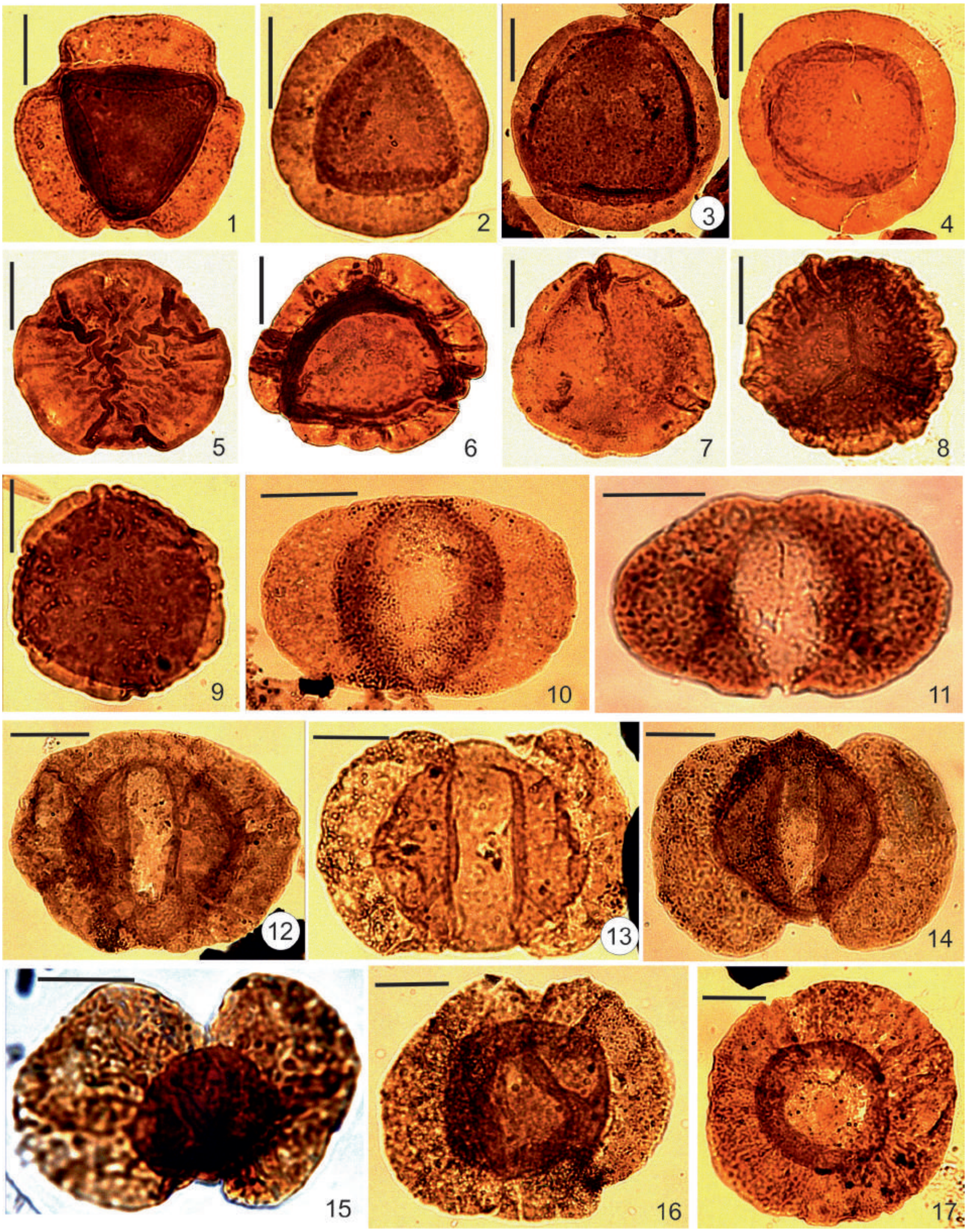

PLATE 2

THERMALLY ALTERED SPORES, POLLEN GRAINS AND SPOROPHYLLS

Spores and pollen grains (shown in Pls 1–3) are highly sensitive to the high temperature than other plant organs. Microsporophylls of pteridophytes, which were affected by the high temperature during forest fire, are not altered much as shown in three–dimensional images under scanning electron microscope (Pl. 4.13, 14). Spores embodied in the sporophyll or liberated from it exhibit cracking in their exine, amalgamation in exinal sculptures and darkening of colour from pale yellow to brown or black (Pl. 3.1–4). Such morphological changes occurred due to carbonization of biopolymers, breakage or cleavage in their organic molecules or coalification of the cytoplasmic contents (Bostic, 1971; Combaz, 1971; Correa, 1971; Gray & Boucot, 1975; Kedves & Kincsek, 1989; Kedves *et al*., 2000). A large number of bisaccate pollen grains showing changes in size and shapes are discernible in their saccus and cappa (Pl. 3.5–12), while non–saccate forms turned into the triangular, sub–circular to oval shapes (Pl. 3.13–25). In these pollen grains shrinking and distortion in the entire body are common (Pl. 3). Changes in morphological features and colours can be easily compared with unaltered spores and pollen grains as shown in Pls 1 and 2.

Other types of sedimentary organic matter (SOM)

Plants or their organs lying away from the heating nooks during forest fire were unaffected or some of them became dry due to the volatilization of protoplasmic fluids. The dried organs or organelles underwent microbial degradation during their burial in sediments after detaching from their parent plant. Quantitative representations of such non–charcoalified plant fragments (termed as sedimentary organic matter or palynofacies, *sensu* Combaz, 1964) with microscopic charcoal in different stratigraphic succession are displayed in Figs 2–7. These sedimentary organic matters categorized into various forms according to the classification proposed by Masran & Pocock (1981), Pocock *et al*., (1988) and Batten (1996) are briefly explained as:

Structured terrestrial–Structured terrestrial organic matter consists mainly of leaf epidermal layers, stomatal apparatus, well–structured vascular tissues of the stem and pieces of roots. These unaltered phytoclasts show distinct morphological and anatomical details and represent 2–20% in the palynofacies assemblage.

Biodegraded terrestrial–The biodegraded phytoclasts are derived from various types of terrestrial plant organs generally affected by microbs (fungi and bacteria) during their burial in sediments. These phytoclasts show degradation of tissues and their cellular structures and represent 2–30% in various stratigraphic successions.

Amorphous–Amorphous organic matter consists of highly biodegraded phytoclasts with no cellular details. It is the result of the extreme microbial breakdown of the structured terrestrial phytoclasts (Pocock *et al*., 1988). Its frequencies range between 1–30% in the various palynofacies assemblage. Its low frequencies in the sedimentary successions indicate lack of suitable biodegradable materials because of insufficient supply of the unaltered phytoclasts from the fire affected biomass at the depositional sites.

Resins–A quite good quantity of resins occur in the form of lumps or globules, which are rounded–oval and rectangular to linear in shapes. Resin exudates from stem barks of the arboreal gymnosperms, and is resistant to the microbial decay. Resins are more susceptible to ignition during the forest fire, because of containing more lipid contents and other inflammable materials (Küçük & Aktepe, 2017). They occur within 2–15% in palynofacies assemblage of the different sections. Their meagre occurrence in some horizons indicates that such flammable materials were burnt out during the forest fire.

Abundance of microscopic charcoal and other SOM in various sedimentary successions

Quantitative analyses of the well–structured microscopic charcoals in various lithotypes of studied sedimentary successions occur at Khareri, Badwar, Patparha and Tekan mining sites around Chandia Town in the South Rewa, along the Pur River Section near Trambou Village and Khari River Section exposed near Bhuj–Sukhpur Road in Kachchh basins

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PLATE 3

(Scale bar = 30 µm) ⟶

Light microscopic images of fossil pteridophytic spores and gymnosperm pollen grains showing alterations in morphology and colour due to the effect of heat during early Cretaceous forest fire.

1–2. Spores of Cyatheaceae/Dicksoniaceae, Slide No. 14469 Q51, C51.
3–4. Spores of Pteridaceae, Slide No. 14457 R23, 14473 R46.
5–25. Gymnosperm pollen grains showing a change in cappa, sacs and size due to the effect of high temperature during forest fire.
5–12. Bisaccate pollen grains, Slide No. 14457, M32, K40, 14470 W40, O42, P35, P29, 14440 J37.
13. Thermally altered pollen grain resembling *Tsugaepollenites* sp., Slide No. 14472 N49.
14–21. *Callialasporites* spp., Slide No. 14469, Q51, P51, 14470 N29, 14479 F29, 14473 T31, 14480 J38, 14469 Y42.
22–24. Thermally altered pollen grains are showing resemblances with *Araucariacites* spp., Slide No. 14464 M45, 14469 M42, 14470 O31.
25. Thermally altered Cycadalean pollen grain, Slide No. 14469 C51.

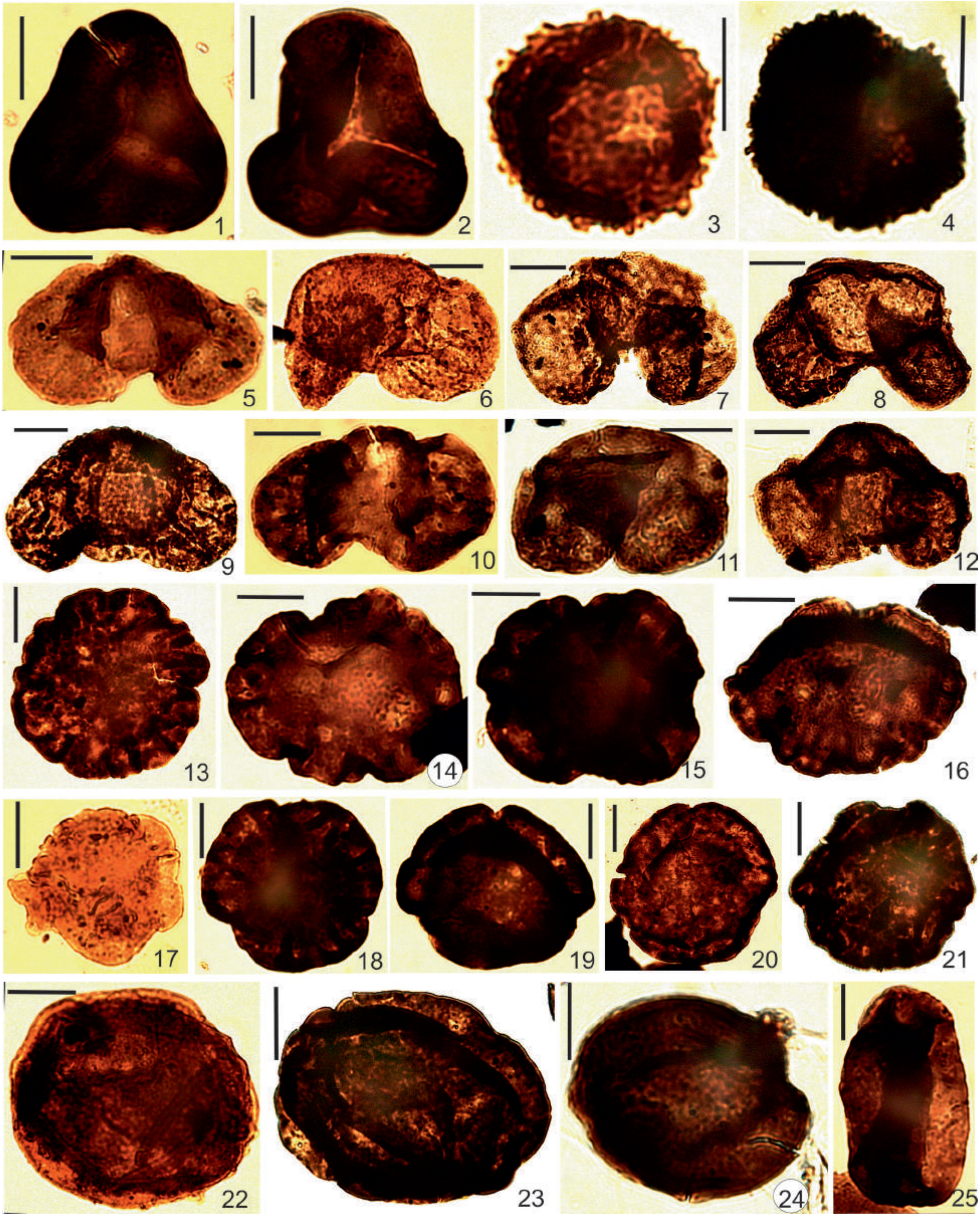

PLATE 3

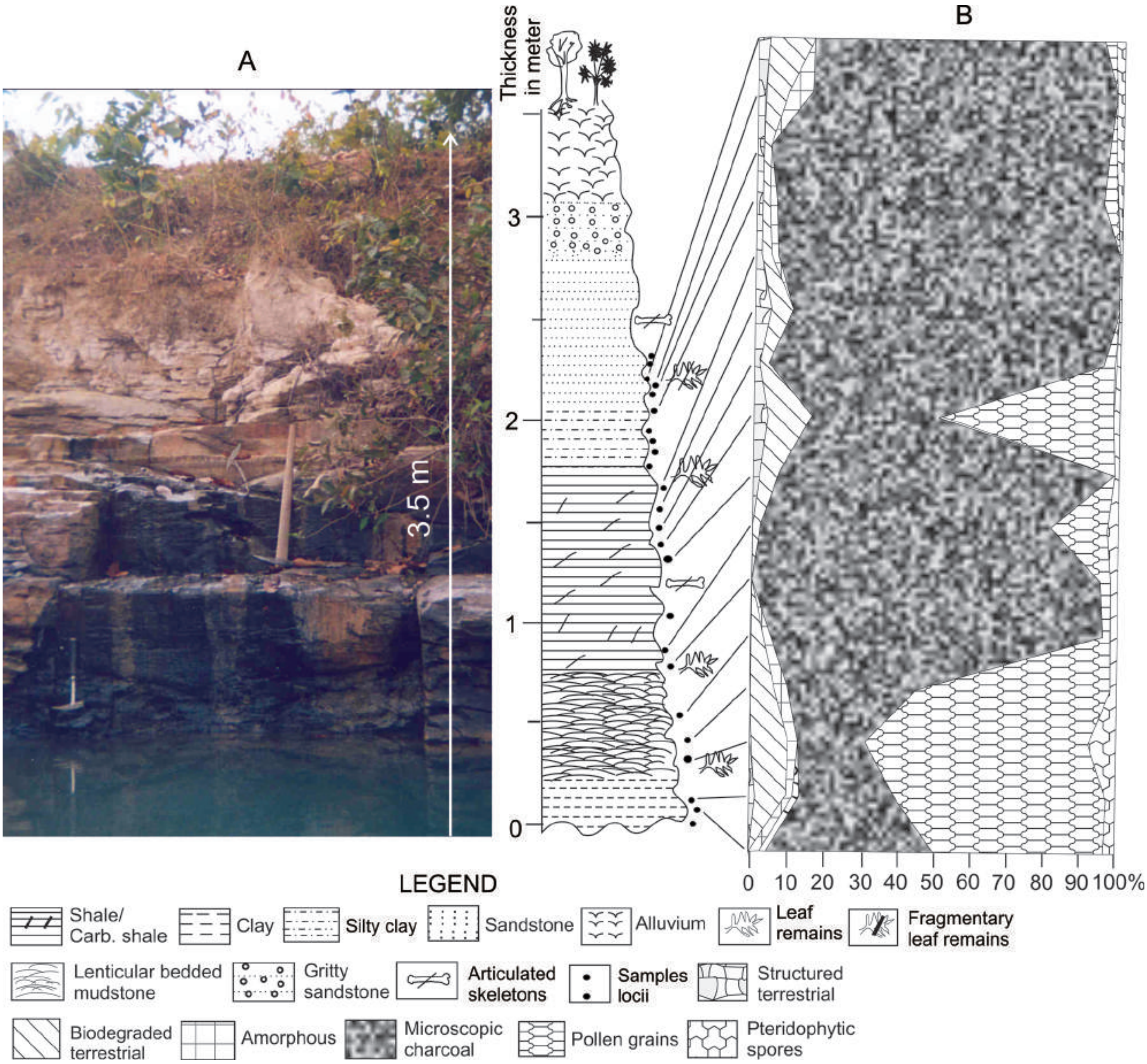

Fig. 5—Photograph showing charcoal bearing section exposed at Tekan in the South Rewa Basin, lithology and frequency of sedimentary organic matter; A. Image of the exposed mine pit section; B. Abundance of microscopic charcoals, spores/pollen grains and other sedimentary organic matter in various samples collected from the section.

PLATE 4

Scanning electron microscopic (SEM) images of the charcoalified pieces of gymnosperm woods →

1. Charcoalified piece of conifer wood in tangential longitudinal view.
2. Enlarged veiw of figure 1 showing rays and vascular tissues (arrow marked).
3. A charcoalified piece of stem showing sclerenchymatous tissue.
4. Distorted tracheids and pits.

5–6. An enlarged view of homogenized cell walls and rupturing of the vascular tissues (→ marked) showing an amalgamation of protoplasmic contents due to the effect of intensive heat during a wildfire.

7. Tangential longitudinal view of a charcoalified piece of wood showing thermally altered tracheids and bordered pits.

8–9. An enlarged view of G showing rupturing of rays and pits (→ marked).

10. Transverse view of charcoalified vascular tissues of conifer stem.
11. Magnified view of figure 10 showing thick walled phloem parenchyma, distortion in vessel elements and cell lumens filled with transformed carbon crystals and spherules.
12. Amalgamation of protoplasmic materials in parenchymatous cells due high–temperature effect.
13. Thermally altered mesofossil of a fern sporangium.
14. Enlarged view of figure 13 showing morphologically distorted spores inside the sporangium.
15. charcoalified piece of stem showing distorted pits and amalgamation in tissues.

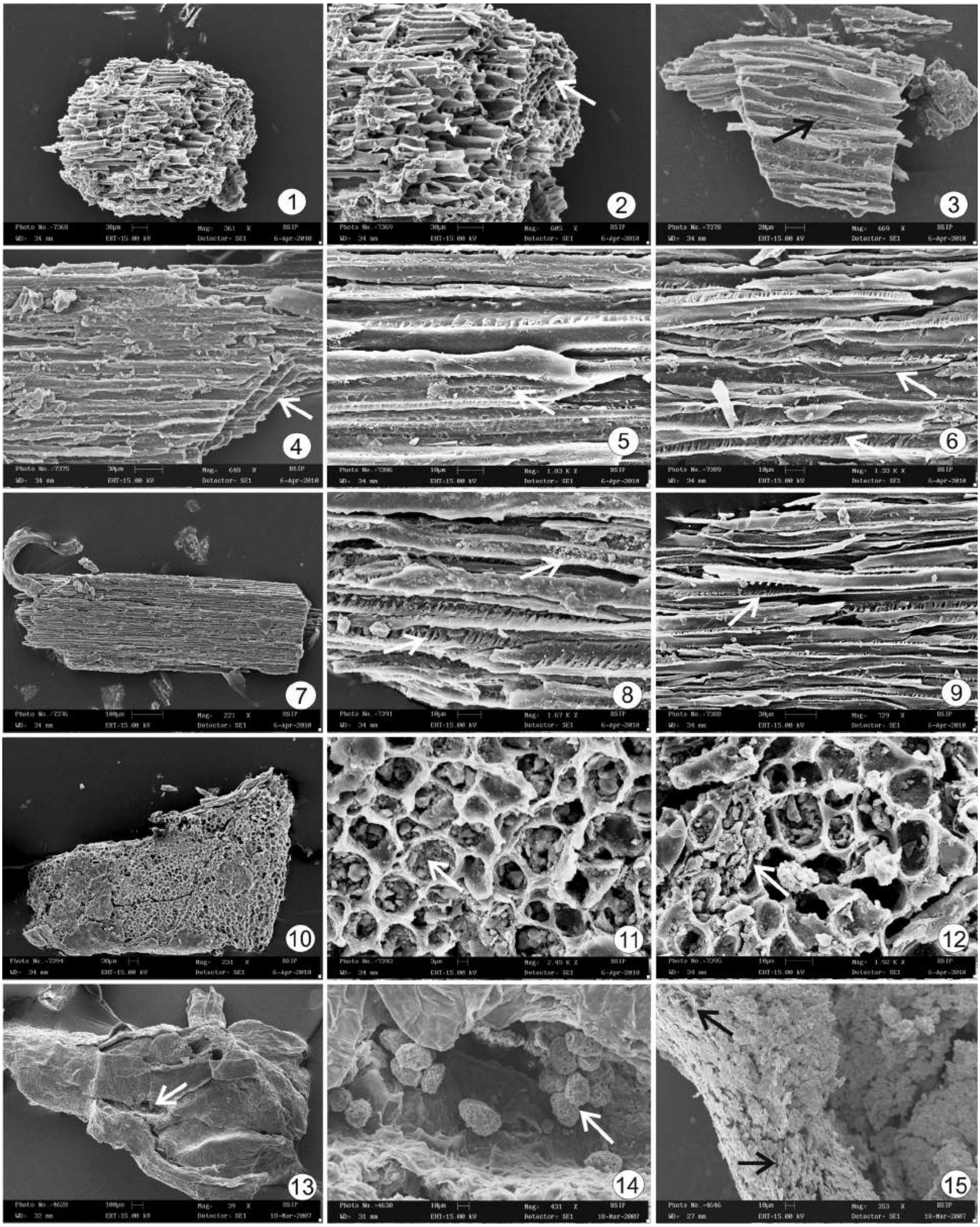

PLATE 4

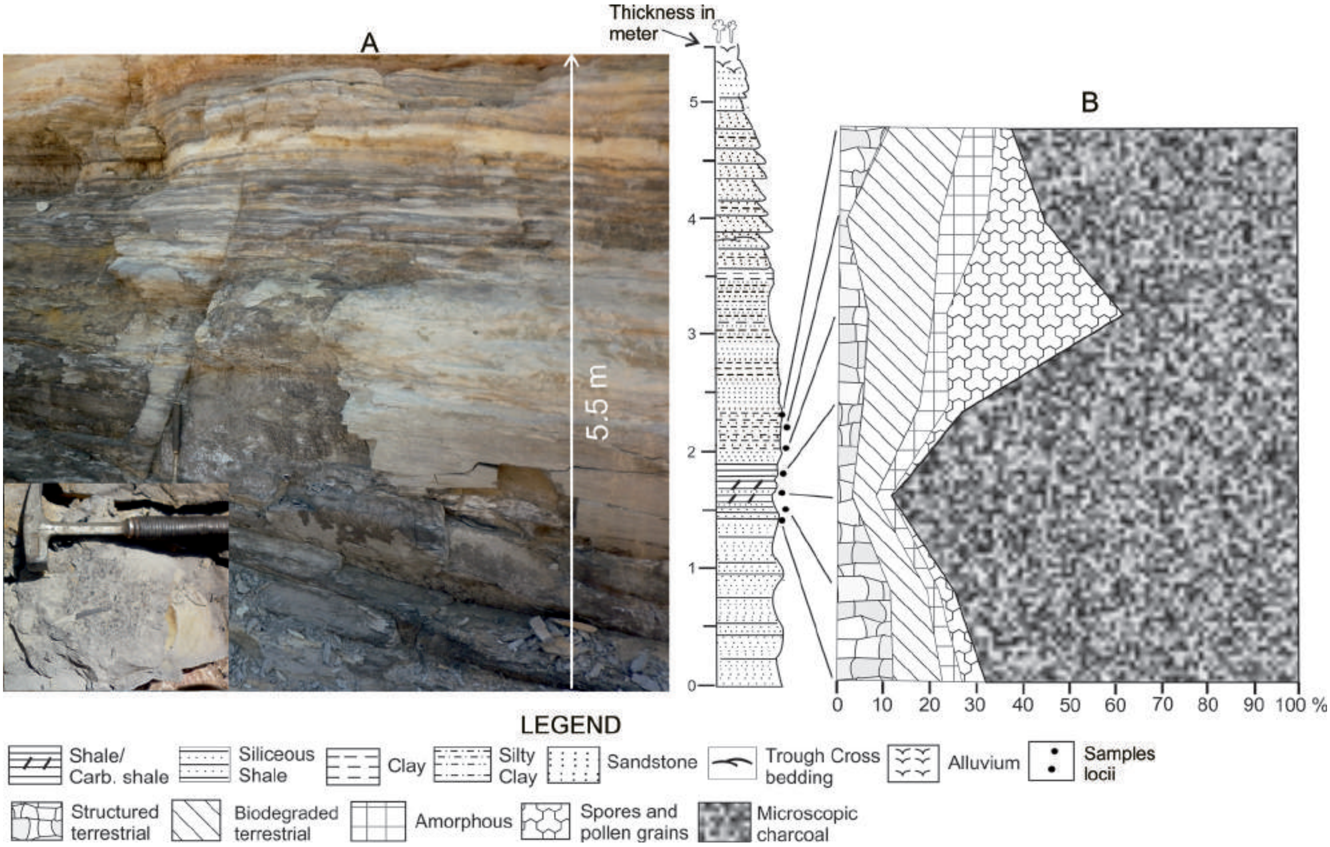

Fig. 6—Photograph showing charcoal bearing section exposed at Trambau in the Kachchh Basin of northwestern India, lithology and frequency of sedimentary organic matter; A. Image of the exposed mine pit section and inset photograph showing pieces of macroscopic charcoalified plant remains; B. Abundances of microscopic charcoals, spores/pollen grains and other sedimentary organic matter in various samples collected from the section.

have been carried out. Abundance of microscopic charcoal in various stratigraphic horizons indicates frequency of their dispersal during deposition in lakes or other accomodating sites. Sedimentary successions of various localities which are bearing microscopic charcoal and other phytoclasts are mentioned below.

Khareri–A 2.2 m thick section exposed on both sides of the Machrar River (Lat. 23º09'09" N: Long. 80º40'12" E) near a small village Khareri, situated at 8 km north of the Chandia Town. The section comprises 25 cm thick sandstone at the base, which is overlain by 0.6 m thick lenticular–bedded mudstone, 0.8 m thick compact sandstone, 0.4 m thick carbonaceous shale and 0.2 m thick layer of greyish shale (Fig.

PLATE 5

Charcoalified pieces of leaves and stems (scale bar = 100 µm, unless otherwise mentioned) showing morphological distortion due to thermal effect during a wildfire. →

1. Charred apex of the young araucarian microphyllous leaves with opposites decussate arrangement, Slide No. 14461 K25.
2. A portion of the apex of the young crozier of fern, Slide No. 14466 R26.
3. Open stoma, guard and accessory cells in a piece of thermally altered gymnospermous leaf.
4. Hexagonal parenchymatous cells in a piece of woody stem, Slide No. 14459 Q30.
5. Upper epidermal tissue of gymnosperm leaf showing rupturing due to loss of protoplasmic fluids and tension in cell lamella.
6. Cross–field pitting and distorted tracheids of a piece of conifer wood, Slide No. 14467Q28.
7. A piece of charcoalified araucarian wood in radial longitudinal view showing scalariform thickening and biseriate bordered pits, Slide No. 14479 T29.
8. Spirally thickened vascular system of a piece of wood, Slide No. 14461 L35.
9. Open stoma and guard cells in a carbonized piece of leaf, Slide No. 14473 T29.

10–11, 15. Tracheids, perforated after thermal effect during wildfire Slide No. 14466 R6, 14465 N27.

12. Highly altered and ruptured tracheids, rays, etc. in charcoalified vascular tissue of gymnospermous wood.

13, 16–18. Perforated gymnospermous woody tissues due to various phases of alteration by intensive heat effect, Slide No. 14462 H17, 14475 K29, 14479 U53, 14476.

14. Charred needle–shaped leaf pieces and other tissues.

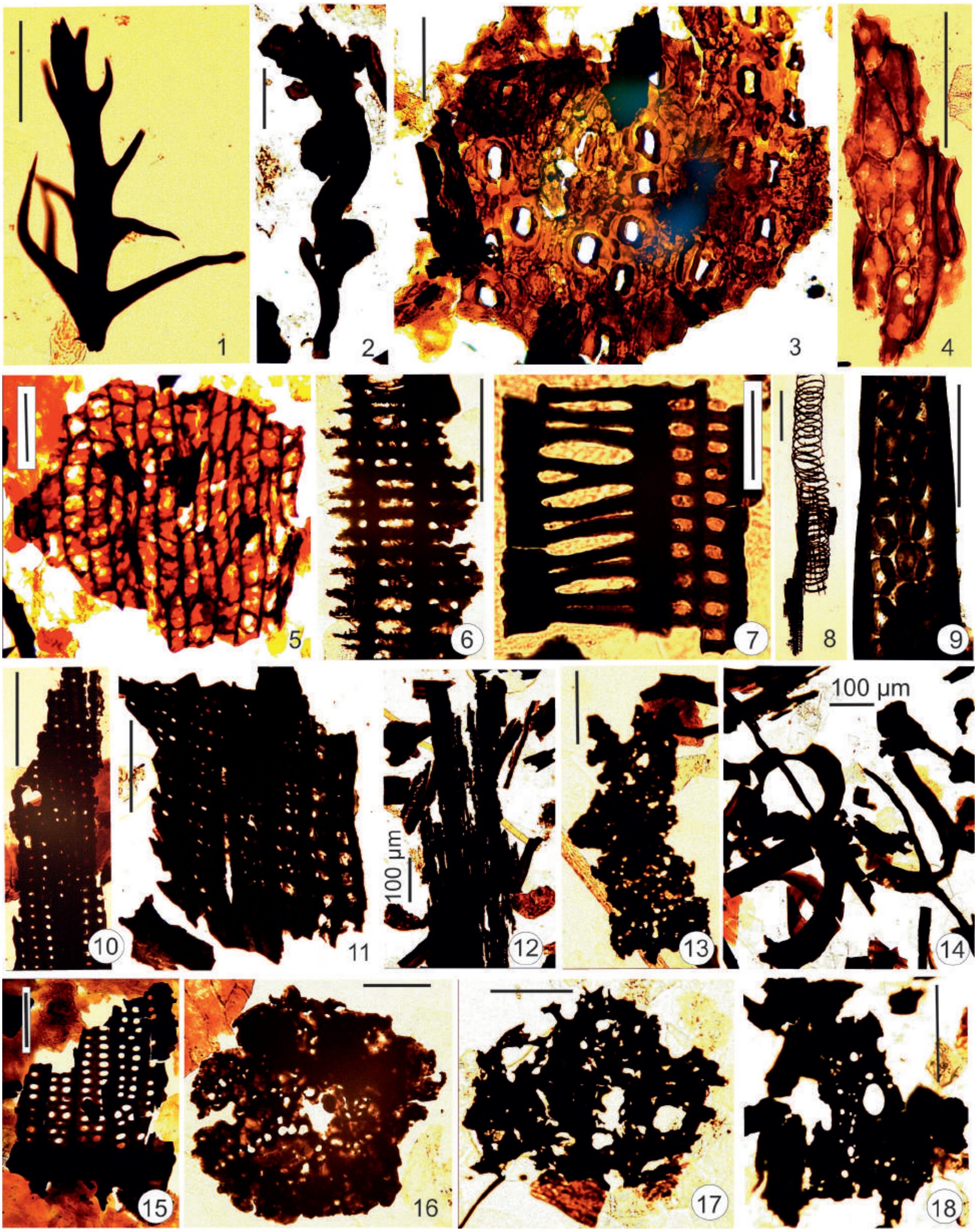

PLATE 5

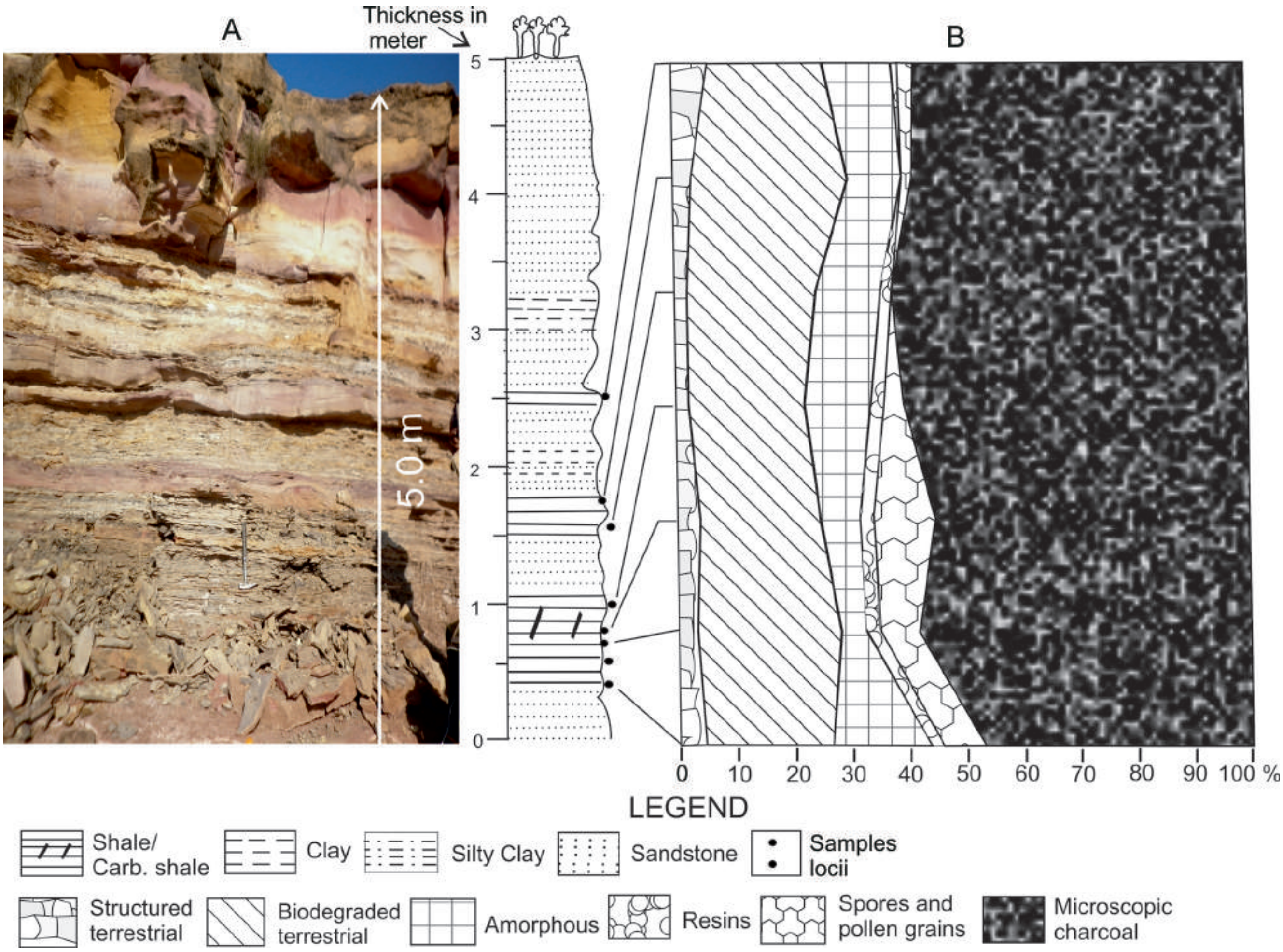

Fig. 7—Photograph showing charcoal bearing section exposed along Khari River in the Kachchh Basin of northwestern India, lithology and frequency of sedimentary organic matter; A. Image of the exposed section, B. Abundance of microscopic charcoals, spores/pollen grains and other sedimentary organic matter in various samples collected from the section.

2). The lenticular–bedded mudstone embodies fragmentary leaf remains of conifers and pteridophytes. These fossiliferous beds are covered by 0.5 m thick loose sandstone and variably thickened alluviums.

The basal lenticular–bedded mudstone contains 57–60% microscopic charcoal. Its abundance is varying between 15–83% in upper part of the carbonaceous shale (Fig. 7B). Spores and pollen grains represent 2% in the lower part and up to 40% in the upper carbonaceous shale of the section; thereby indicating growth of the luxuriant ferns and other pteridophytes, conifers and cycads during deposition. Structured terrestrial organic matter represents 2% at the base and increases between 10–15% towards the top of the section. Biodegraded terrestrial occurs 25%, while amorphous represents 10–20% at the base and 5–10% in the upper part of the section. Occurrence of 50–60% microscopic charcoal in the lower and middle parts exhibits input of the abundant burnt materials at the site of deposition. Representation of more than 10–20% resin globules in the lower part of the lenticular–bedded mudstone and decrease in its quantity up to 2–5 percent in the upper part indicate burning of resin–producing arboreal gymnosperms. The upper carbonaceous shale exhibits further increase of charcoalified materials from 15 to 83% indicating further supply of the increased quantity of plant fragments derived from the fire–affected vegetation.

Badwar–Badwar clay quarry (Lat. 23º37'12" N: Long. 80º44'07" E) is exposed at the right side of the Chandia–Umaria road at a distance of five km south of the Chandia Town. A 4.5 m thick section comprises 0.2 m thick shale at the bottom, which is overlain by 0.5 m thick brownish clay, 0.7 m thick carbonaceous shale, 0.4 m thick dirty brown shale, 0.4 m thick sandstone and 1.5–2.5 m thick alluviums towards the top (Fig. 3A). The clay, carbonaceous shale and brownish clay beds embody numerous 5–40 cm long charcoalified twigs (Fig. 3C1). The upper dirty brown shale contains charcoalified araucarians cones and charred fragmented leaf remains (Fig. 3C2–C4). A large number of thermally altered spores and pollen grains recorded in these lithotypes indicate impact of the rigorous fire, which destroyed entire vegetation in this area. The upper carbonaceous clay bed exhibits 25–30% microscopic charcoal at the lower part with an increase of 70–75% in the upper part. The abundance of microscopic charcoal is progressively increased up to 93% in uppermost clay–shale beds. A few unaltered pollen grains belonging to the family Araucariaceae, Podocarpaceae and Cycadaceae are recorded in the topmost clay bed. Other types of sedimentary organic matter, viz. structured terrestrial, biodegraded and amorphous occur in low frequency (1%) at the bottom and enhance up to 5% in the dirty brown shale and greenish clay in upper part of the section (Fig. 3B).

Patparha–Patparha clay quarry (Lat. 23º38'00" N: Long. 80º44'12" E) is situated at a distance of 3 km from Chandia Town on the left side of Chandia–Umaria road. A 5.5 m deep pit section exposed in a clay quarry comprises 0.9 m thick carbonaceous shale, which is sandwiched between 0.5 m thick clay at the top and 0.6 m thick beds at the bottom. The 40 cm thick fine–grained clay occurring at 2–3 m height from the base comprises rich micro–and fragmentary megascopic charcoalified plant remains. The upper greyish clay and thin white siliceous clay beds are devoid of any fossil contents. These beds are overlain by loose sandstone and alluvium (Fig. 4A). The shale and carbonaceous shale at the bottom comprise ~ 2.5 cm long fragmentary leaf remains, various sizes of charcoalified pieces of stems and twigs of the arboreal gymnosperms. Microscopic charcoal present in quite higher frequency (82%) in the basal carbonaceous shale and decrease up to 50% in the middle part of the section. A further increase in their frequency up to 85% is noticed in the upper part of the section. Thermally altered spores, pollen grains (2–3%) and resinous materials (2–5%) uniformly occur in the section. A decreasing trend of structured terrestrial (17–12%) and amorphous (32–27 %) organic matter recorded in the section is shown in Fig. 4B.

Tekan–Taken clay quarry (Lat. 23º41'35" N: Long. 80º47'20" E) is situated 8 km northeast of the Chandia Town. A 3.5 m thick sedimentary succession exposed in mining pit near a small tributary of the Mahanadi River, comprises 0.6 m thick compact sandstone at the bottom and 0.8 m thick fine lenticular bedded mudstone in the middle and 1.0 m thick carbonaceous shale towards the top (Fig. 5A). The mudstone and carbonaceous shale beds embody complete to fragmented leaf remains and a few unidentified articulated and poorly preserved silicified tetrapod skeletons. The well–stratified upper carbonaceous shale also contains a large number of fragmentary leaf remains and abundant microscopic charcoal. These fossiliferous strata are overlying 0.8–1.0 m thick loose nodular sandstones, 0.3 m thick gritty sandstone and 1.0–1.5 m thick alluvium. The loose sandstone bed occurs at the top of the section also embodying silicified articulated tetrapod skeletons.

The lenticular bedded mudstones and well stratified carbonaceous shale exposed at the base of the section represent 25–40% microscopic charcoal, which increases up to 90% in the upper part of the section. Palynofloral remains comprise 2–3% pteridophytic spores (*Cyathidites* spp., *Contignisporites glebulentus*, *Dictyophyllidites crenatus* and *Gleichenidites senonicus*) and 50–60% pollen grains (comprised by *Araucariacites* spp., *Callialasporites* sp., *Alisporites* spp. and *Cycadopites couperi*) in the mudstone lying between 0–1.0 m height from the base. A decrease in the frequency of pollen grains between 4–8% is noticed in the upper part of the carbonaceous shale and clay, while pteridophytic spores show uniform distribution (2–3%) throughout the section. Uniform distribution of the spores exhibits a continuous proliferation of the pteridophytes, which were colonizing away from the fire–affected vegetation. The structured, biodegraded terrestrial and amorphous organic matters occur with 2–10% in this section (Fig. 5B). No resin globule was recorded from this fossiliferous sedimentary succession.

Pur River Section, *Trambau*–Trambou Village is situated at a distance of 18 km from Bhuj Town towards northeastern side in the Kachchh Basin. A 5.5 m thick section is exposed in a mining pit site near the village (Lat. 23º19'29" N: Long. 69º49'59" E) along the seasonally flowing Pur River. The river cutting section comprises 1.45 m thick sandstone and 0.5 cm thick shale at the bottom and 0.5 m thick carbonaceous shale, 0.1 m thick sandstone and 0.4 thick silty clay bed towards the top. The 1.5 m thick shale–clay alternations is overlying trough cross–bedding of sandstone, variably thickened loose sandstone, clays and 0.2–0.4 m thick alluviums towards the top of the section (Fig. 6A).

The basal carbonaceous shale and silty clay beds comprise 68–85% microscopic charcoal, which decreases its frequency up to 60% in upper part of the section. The other organic matter, viz. structured terrestrial 2–12%, biodegraded terrestrial and amorphous represent 5–20 and 3–10% respectively. Spores, megaspores and pollen grains occur with 2–4% in the carbonaceous shale and 5–30 percent in its overlying silty clay bed (Figure 6B). Larger pieces of charcoalified plant remains with size range between 0.2–6.5 cm x 0.2–1.5 cm are abundantly occur in the carbonaceous shale bed (inset in Fig 6A).

Khari River section–A clay quarry site (Lat. 23º14'71" N: Long. 69º37'50" E) situated along the Khari River (Fig. 7 A) at the distance of 26 km from the Bhuj Town near Bhuj–Sukhpur Road, comprises 0.5 m thick sandstone at the base, 0.5 m thick carbonaceous shale, 0.45 m thick sandstone and 0.3 m thick greyish shale in the middle part. Many charcoalified pieces between 0.2–1.0 cm in sizes occur abundantly in these lithotypes. These fossiliferous strata are overlain by 1.5 m thick sandstone, 0.25 m thick silty clay and 1.75 m thick sandstone towards the top. The carbonaceous shale and upper greyish shale contain 45–60% microscopic charcoal. The other sedimentary organic matter i.e. structured terrestrial 2–3 %, biodegraded terrestrial 20–26% and resins 2% only.

Amorphous organic matter represents 5–15%, while spores and pollen grains 5–10% only (Fig. 7B).

Sedimentary successions occur in above mentioned areas embody characteristic evidences of fire events and their products in the form of the microscopic charcoal. Their abundances in all sedimentary successions are helpful for comparing the changes in abundance and processes of their accumulation in lakes or other accommodating sites. These results pointing out severity of wildfire in various areas are related with their production from affected vegetation and accumulation at various sites, landscape features and depositional environment.

DISCUSSION

Age of the charcoal bearing horizons

Early Cretaceous sedimentary horizons in South Rewa and Kachchh basins have yielded plant fossils and majority of them are similar to those recorded from Australia, Antarctica and other Gondwanan continents (Bose & Shukh–Dev, 1959; Bose & Banerjee, 1984; McLoughlin, 1996, 2001; Kumar, 2018). Sedimentary successions of the Bansa Formation in South Rewa Basin is predominantly non–marine, while equivalent horizons of Bhuj Formation in Kachchh Basin are both marine and non–marine deposits. Depositional processes of marine and non–marine sediments in these basins were controlled not only by consequences of the break–up of India from Gondwana, but also by a change in the direction of rotation of Indian Peninsula moving towards Asia (Norton & Sclater, 1979; Biswas, 1987; Babu, 2006). The palynoflora of non–marine Early Cretaceous sediments of South Rewa and Kachchh basins are similar with a few exceptions; but for correlating sedimentary sequences, a detailed study based on the distinctive and unique time marker fossils of the same age is required. Both the basins have no record of recycling of older deposits, so no question arises about their antiquity. Record of wildfires in these basins is much significant and considered as unique phenomenon in the Early Cretaceous because such phenomenon simultaneously destroyed the vegetation spreading in a wider area, providing an almost instantaneous equal time marker event. Thus, fossiliferous sedimentary successions which preserve a large number of fossil flora affected by wildfires in both the basins, are extremely significant.

Age of the Bansa Formation is based on the mega– and microscopic plant fossil records. Bose and Sukh–Dev (1959) recorded characteristic leaf impressions of *Weichelia*, *Onchiopsis,* and *Ptilophyllum* from the sediments exposed near Chandia Town (Lat. 23º39'22" N: Long. 80º42'43" E) and postulated its similarities with Wealden flora of the England. Maheshwari (1974) recognized *Podocarpidites–Cycadopites–Properipollenites* assemblage sub–zone in the sedimentary succession of Bansa Formation and assigned Early Cretaceous age. Pteridophytic spores, viz. *Contignisporites glebulentus*, *Retitriletes tennuis, Ruffordiaspora australiensis*, *Streisporites viriousus* and pollen grains of *Podocarpidites* spp., *Alisporites grandis*, *Araucariacites* spp. and *Callialasporites* spp., recorded from the Bansa Formation are also reported in other late Neocomian–Aptian palynoassemblage of Rajmahal and Satpura Gondwana basins of India (Bhardwaj *et al*., 1972; Vijaya, 1997) and Early Cretaceous sediments in south–eastern, western, Eromanga and Surat basins of Australia (Dettmann, 1963; Dettmann & Playford, 1969; Burger, 1980; Sajjadi & Playford, 2002a, b). The Jabalpur Formation in the adjacent Satpura Basin is older (Late Neocomian–Aptian) than the Bansa Formation, as evident by mega–and microfloral record of Shah *et al*. (1971), Bhardwaj *et al*. (1972), Prakash (2008) and Kumar (2011).

Sedimentary successions of the Bhuj Formation show rich palynomorphs especially dinoflagellate cysts– *Coronifera oceanica, Oligosphaeridium pulcherrimum*, *Prolixosphaeridium parvispinum* and *Stiphrosphaeridium anthophorum* (Kumar, 2018) with global nanoplankton markers *Prediscosphaera columnata* and *Tranolithus orionatus* (Rai, 2006) of the Aptian–Albian age. Mude *et al.* (2012) reported ichnofossils *Palaeophycus heberti*, *P. tubularis* and *Skolithos linearis* from the Bhuj Formation and assigned Late Aptian–Early Albian age. The upper Bhuj Member is normally devoid of marine macro–or micro–fauna considered as fluvial deposits (Biswas, 1977).

Consequences and causes of the palaeofire

Microscopic charcoal recorded from the Early Cretaceous sediments of both the basins may be linked with the burning of the existing vegetation due to nearby volcanic activities and regional palaeoclimatic changes. These charcoalified plant remains in various geologic archives can be used as an indicator and recorder of ancient volcanic or other violent hazardous fire impacts on the continental biomass, which were buried in sediments and considered as most important carbon pools and carbon sink ecosystems (Cordeiro *et al*., 2015). It is understood that during geologic pasts forests were ignited through–(i) volcanic activities and the eruption of fireballs, (ii) lightning strikes and sparkling, or (iii) by extraterrestrial meteoritic effects (Jones & Lim, 2000; Scott, 2000; Uhl *et al*., 2004). Ignition possibility through extraterrestrial meteoritic materials is much controversial (Jones & Lim, 2000). Lightning may ignite non–moist vegetation with low intensity by thundering and electric rays, responsible for one or more short phases of wildfires. Plants once ignited by the thundering electric rays during lightening burn out standing vegetation, but extinguished mostly by ensuing rainstorms (Scott, 2000). The hot lava and other pyroclastic flow or eruptions of volcanic bombs during the volcanic activities are considered to have great potentiality for igniting wildfires (Scott, 2000, 2010; Uhl *et al*., 2004). Frey *et al*. (1996) opined that during

Table 1—The botanical affinity of some spore–pollen taxa with nearest modern relatives and their occurrence in South Rewa and Kachchh basins (+ present,– absent). The relationship of fossil spore–pollen taxa with modern plants is based on the interpretations made by Dettmann (1963), Dettmann & Playford (1969), Maheshwari (1974), Tryon & Tryon (1982), Balme (1995), Abbink *et al.* (2004) and Schrank (2015).

Palynotaxa	Botanical affinity	South Rewa	Kachchh
Microspores			
Cyathidites australis, *C. minor, Concavissimisporites variverrucosus*	Cyatheaceae/Dicksoniaceae	+	+
Gleichenidites senonicus, *Dictyosporites* sp.	Gleicheniaceae	–	+
Dictyophyllidites crenatus, Biretisporites spectabilis	Matoniaceae	+	+
Laevigatosporites ovatus, Densoisporites velotus	Polypodiaceae	+	–
Contignisporites cooksonii, *C. glebulentus, Cicatricosisporites ludbrooki, Coupersporites complexus, Ruffordia australiensis* and *Klukisporites scabris*	Schizaeaceae (*Anemia/Mohria/ Ruffordia*)	+	+
Lycopodiumsporites nodosus, Foveosporites sp., *L. austroclavatidites*, *Foraminisporis asymmetricus* and *Retitriletes nodosus*	Lycopodiaceae	+	+
Megaspores			
Minerisporites spp., *Paxilitriletes batenii*, *P. fairlightensis*	Selaginellaceae/ Isoetaceae	–	+
Pollen grains			
Araucariacites australis, *Callialasporites dampieri*, *C. trilobatus*, *C. barragaonensis, C. discoidalis* and *C. minutus*	Araucariaceae	+	+
Podocarpidites ellipticus	Podocarpaceae	+	+
Tsugaepollenites sp.	Pinaceae		
Alisporites grandis	Pinaceae	+	+
Classopollis classoides	Cherolepidiaceae	–	+
Cycadopites grandis	Cycadales (extinct Cycadeoidales, Bennettitales, Ginkgoales)	+	+

the Early Cretaceous (between ~ 132–117 Ma) widespread volcanism occurred and lava erupted on the continental margin of Greater India, Australia and Antarctica. Mukhopadhyay *et al*. (2010) also postulated that during the Early Cretaceous (Aptian) the volcanic theiolitic lava erupted in India, Western Australia and Antarctica and continued till Albian (125–112 Ma), when Jabalpur, Bansa, Gangapur/Chikalia, Umia, Bhuj and Infra–Rajmahal beds of Indian peninsula came in the existence. Thus, flowing of hot lava or falling of eruptive volcanic bombs was main cause of wildfire which destroyed vegetations of the many Indian basins during Aptian–Albian.

Palaeovegetation, palaeoclimate and palaeoenvironmental interpretations

Interpretations of biomass combustion during wildfire require comparison of the charcoal particle produced and fluxed by various vegetation communities at various time scales (Cordeiro *et al*., 2015). Due to the small size of charcoalified woods and leaf remains with the absence of high valued correlative features, their close affinity with relative plant species is difficult to assess. However, types of vegetation indicated by pteridophytic spores and gymnosperm pollen grains recorded from various sedimentary successions of South Rewa and Kachchh basins enable to establish morphological similarities with plants of arboreal families of Pinales (Araucariaceae, Podocarpaceae, Pinaceae, Cheirolepidiaceae), Ginkgoales, Bennetittales and Cycadeoidales. In the dominant arboreal forest some pteridophytes were represented by members of the families, viz. Cyatheaceae/ Dicksoniaceae, Matoniaceae, Lycopodiaceae, Polypodiaceae, Gleicheniaceae and Schizaeaceae, etc. (Table 1). Such pteridophytes were spreading as creepers or understory shrubs on the forest floor, which constituted a mixed vegetation type in both the basins. High–canopied araucarians, podocarps, mid storied cycads and tree ferns considered as representatives of the evergreen–deciduous forest thrived during deposition of the various horizons. Such vegetation was flourishing luxuriantly in the humid and warm temperate–subtropical climate (Prakash & Kumar, 2005; Kumar, 2018). *Araucaria* and other conifers constituting a major part of the vegetation during late Mesozoic were particularly fire–prone (Harris, 1958; Francis, 1984; Jones & Chaloner, 1991; Falcon–Lang *et al*., 2001, 2012). Harris (1958) and Alvin *et al*. (1981) postulated that plants of high–canopied Araucariaceae played vital roles in propagating flames during a forest fire and contributed well to the production of charcoal. Arboreal gymnosperms, under–canopied cycads, tree ferns and creepers of pteridophytes spreading on the forest floor, were probably ignited by the spreading of volcanic lava near the vegetation or by falling of fireballs. The botanical relationship of recorded palynoflora is mentioned in Table 1.

The quantitative calibrations of charcoalified plant remains in various lithotypes of the sedimentary successions (Figs 2–7) show medium to high peaks, indicating intensity of fire on the vegetation, frequency of charcoal production, their transportation and accommodation in various depositional sites. These charcoalified remains transported toward lakes through rain water; low energy braided river streams or cross–fluvial bars loaded with mud and silts, etc. Small–charcoalified pieces might have been transported to long distances by running water due to their light weight and slowly settled in the lakes (Clark & Royall, 1996). Settling of microscopic charcoal in the lacustrine systems was broadly proportional to the particle size, where larger particles subsided near the affected vegetation and smaller ones carried away from it (Vaughan & Nichols, 1995).

Destroying of vegetation at certain phases of fire and regeneration of juvenile vegetation after its ceasing was a common phenomenon. The fire traits during Phanerozoic eons devastated forests of many dominated plants and allowed growth of the new plants (Glasspool *et al*., 2015). While reconstructing the palaeo–fire history of the Lower Cretaceous of Isle of Wight, England, Collinson *et al*. (2000) postulated that ferns were the most adaptive element survived after forest fires. Ferns, which are bearing underground rhizomes, were spreading to regenerate even above the ground foliage destroyed by the fire (Scott *et al*., 2014). The episode of fire offered a chance for developing another type of vegetation, which was deprived of the necessary nutritional and edaphic materials consumed earlier by the dominant plant communities. After the death of many dominant plants in the fire affected vegetation, its biomass mixed in the soil with an increased amount of the carbon that later converted to nutrients and minerals in soluble forms, may suitable for intake and growth of another type of vegetation (Caon *et al*., 2014). According to Keeley *et al*. (2011), fire enhances adaptive traits in plants, which were injured during devastation by wildfire.

The phenomenon of burning vegetation and its rejuvenation during episodes of fire in the South Rewa and Kachchh basins of India is much similar to those occurred in several basins of the Southern and Northern hemispheres. A large number of charcoalified plant remains recorded from Cretaceous deposits of Africa, Antarctica, Arizona, Australia, Brazil and New Zealand (Finkelstein *et al*., 2005; Pole & Philippe, 2010; Martill *et al*., 2012; Manfroi *et al*., 2015; Muir *et al*., 2015; Atfy *et al*., 2016; dos Santos *et al*., 2016, Carpenter *et al*., 2016; Mays *et al*., 2017) and England, Belgium, Germany, Spain, Portugal, Czech Republic, Hungary, Canada, USA, etc. (Brown *et al*., 2012 and references there in), proved impact of fire on the vegetation. Thus, microscopic charcoal and thermally altered spores and pollen grains recorded from the Early Cretaceous sediments of South Rewa and Kachchh basins prove impact of fire on the vegetation existed in these parts of India.

CONCLUSIONS

Abundant charcoalified plant remains; thermally altered/non–altered spores, pollen grains and other sedimentary organic matter recorded from sediments of Bansa and Bhuj formations (Early Cretaceous) of South Rewa and Kachchh basins substantiate evidence of fire on the Early Cretaceous vegetation

The relative abundances of well–preserved microscopic charcoal with other types of sedimentary organic matter indicate their transportation and deposition through low energy fluvial processes.

The botanical relationship of significant spores and pollen grains and well–structured morphology of microscopic charcoal indicate that the affected vegetation was constituted by a mix–arboreal gymnosperms, Bennettitales, herbaceous lycophytes, ferns and tree ferns, etc.

The fire–affected vegetation was thriving in humid and warm temperate climate.

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