

percentage of fruits even in the absence of insects and shows no decline in fruit set in bagged inflorescence. Outcrossing is interestingly evaded by *C. mysorensis* as flowers are vesperal in nature, open between 4:45 and 5:30 p.m. for just 3–4 h and there are no insect visits.

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## Macro-charcoal in carbonaceous strata of the Lower Cretaceous of northwest India: remains from the Than Formation, Saurashtra Basin, Gujarat

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**The record of Cretaceous palaeo-wildfires is rather scarce for peninsular India. We aim to report a detailed macro-charcoal analysis as evidence for palaeo wildfires of Early Cretaceous deposits from India. The macro-charcoal was studied using SEM and classified into three morphotypes based on anatomical characteristics. All morphotypes are probably associated with gymnosperms. These findings constitute a record of macro-charcoal and consequently of palaeo-wildfires for the Lower Cretaceous strata of the Saurashtra Basin, Northwest India.**

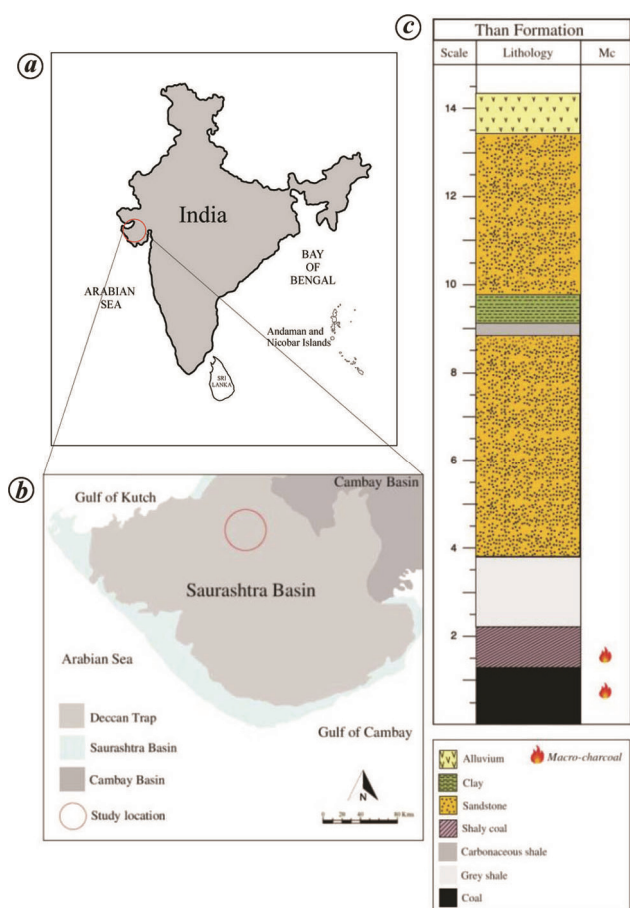
**Keywords:** Carbonaceous strata, gymnosperms, macro-charcoal, morphotypes, palaeo-wildfires.

WILDFIRES are common events in modern and past ecosystems, being a significant evolutionary driver of biodiversity and ecosystem dynamics since the Silurian<sup>1–3</sup>. After fire, plants that did not undergo complete combustion may be preserved as charcoal which can be incorporated in the sediments, and thus can provide direct evidence for the occurrence of palaeo-wildfires in recent and deep time environments<sup>4</sup>. The study of such records enables conclusions concerning the composition of the vegetation affected by fire and some of the palaeoenvironmental conditions of the surrounding areas<sup>5</sup>. Considering fossil macro charcoal, only a few records have been published for Indian strata and they mostly originate from the Permian deposits<sup>6–10</sup>. Although the Cretaceous is globally considered a high-fire interval<sup>11,12</sup>, only a single macro-charcoal<sup>13</sup> and two micro-charcoal<sup>14</sup> occurrences have been published so far for that interval from India. Taking into account the current lack of data about palaeo-wildfire occurrences for the Cretaceous of India and the

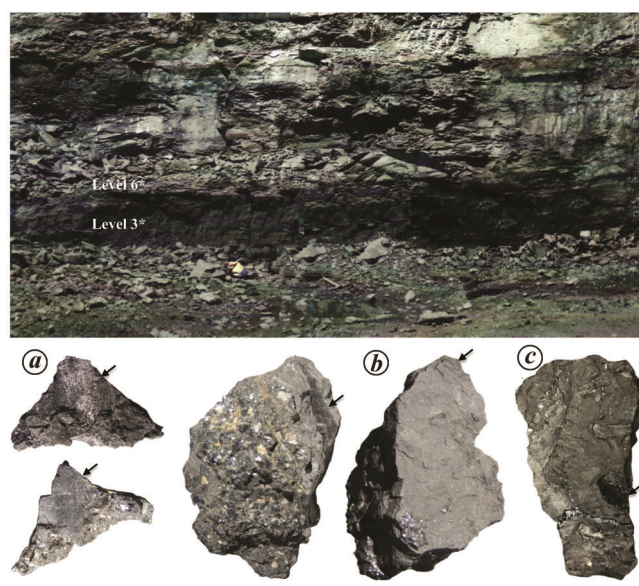
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significance of palaeo wildfire studies for palaeoenvironmental interpretations of this important interval, we present here a record of macro-charcoal from the Lower Cretaceous deposits of the Saurashtra Basin of northwest India (Figure 1 *a*). The Saurashtra Basin is a pericratonic basin that developed at the western margin of the Indian Plate during the separation from the rest of Gondwanaland throughout the Jurassic–Lower Cretaceous<sup>15,16</sup>. The block was part of an extensive peri-continental platform and was surrounded by the Kutch, Cambay and Narmada basins. An extensive fluvio-deltaic sedimentation took place in this area during the Early Cretaceous, and was later intruded and covered by the Deccan Trap igneous rocks during the Late Cretaceous–Early Cenozoic. The Lower Cretaceous Dhrangadhra Group is exposed as an inlier in the Deccan Trap igneous rocks on the northern side of the basin<sup>17</sup>. The Mesozoic rocks of Surendranagar district, Gujarat, India which overlie the Early Proterozoic basement and underlie the Deccan basalt/igneous rocks are interpreted to record the infilling of an Early Cretaceous failed rift<sup>18</sup>. The rift-fill comprises four formations from the

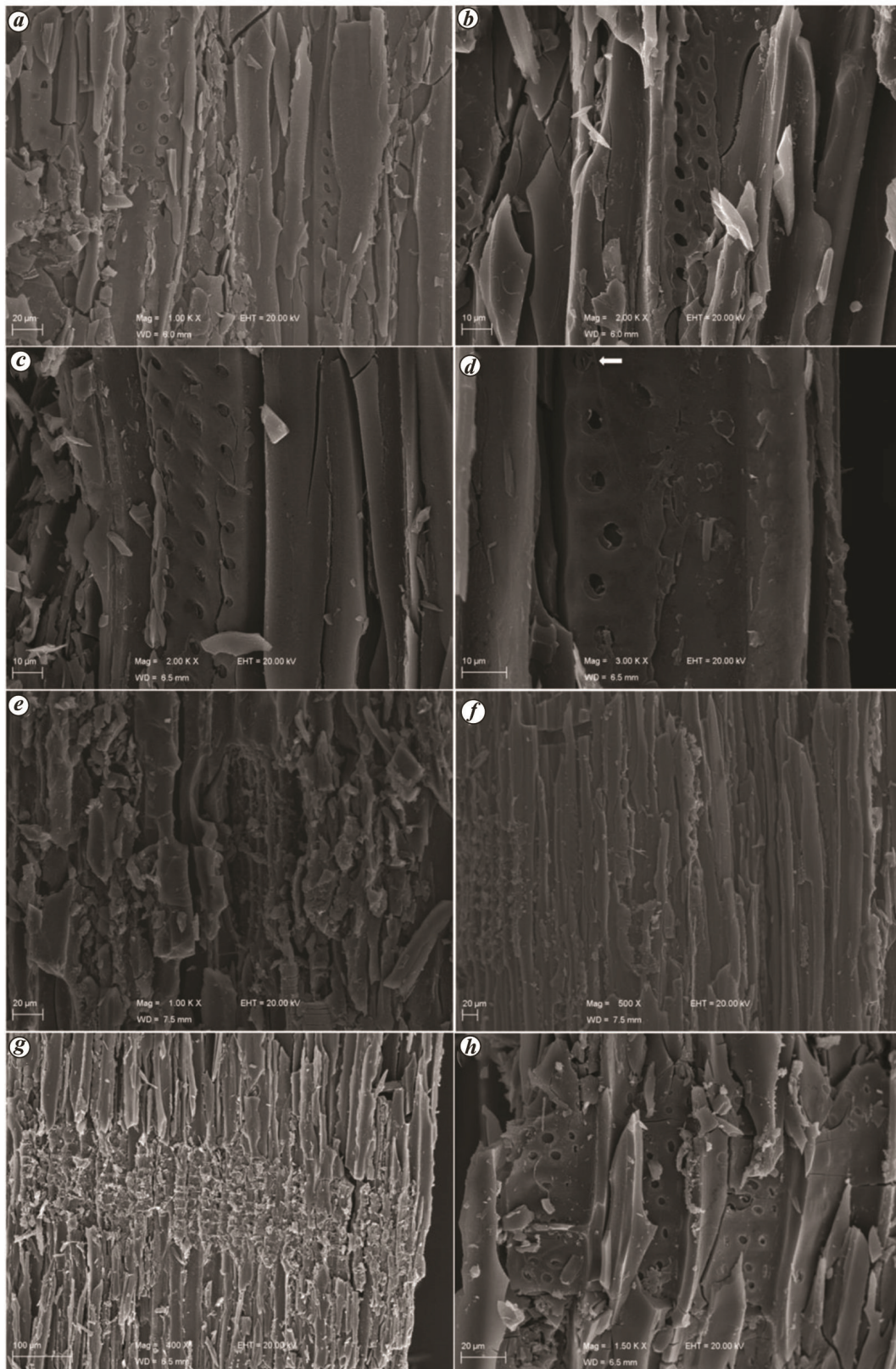
base to the top: Than, Surajdeval, Ranipat and Wadhwan. The Than Formation is a coal-bearing sequence composed of a coarsening upward succession of grey carbonaceous shale, including stringers of coal (Figure 1 *b*) interpreted to be the deposits of delta distributary channels and swamps in the proximity of the shoreline<sup>19,20</sup>, that accumulated during the Barremian–Aptian<sup>20</sup>. Palaeobotanists working at the Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow collected hand samples of carbonaceous shale bands exposed in the surroundings of Thangadh, Gujarat (coordinates 22.25; 70.4166667). To perform the macro-charcoal study, the material was sent to the Laboratório de Paleobotânica e Evolução de Biomas of the Museu de Ciências at the Universidade do Vale do Taquari – Univates, Brazil, where it is stored under the acronym PbUMCN (1296–1299). Fragments with diagnostic features of charcoal (black colour and streak, as well as a silky lustre<sup>1,4,21</sup>) were observed under a stereomicroscope (Zeiss SteREO Discovery, V12) and mechanically extracted from the sediment with the aid of preparation needles and tweezers. Next they were mounted on standard stubs with LeitConducting glue (Plano GmbH, Wetzlar, Germany; www.plano-em.de) and observed under a scanning electron microscope (SEM; Zeiss EVO LS15). Captured images were analysed using the ImageJ software<sup>22</sup> with a calibrated scale bar for measurements. Macro-charcoal fragments with non-abraded edges and varying between 0.14 and 0.67 cm in thickness, 0.47 and 1.71 cm in width, 0.20 and 1.83 cm in length could be recovered from the samples (Figure 2). Under SEM, well-preserved anatomical details, including homogenized cell walls, another distinctive character of charcoal<sup>4</sup>, could be observed.



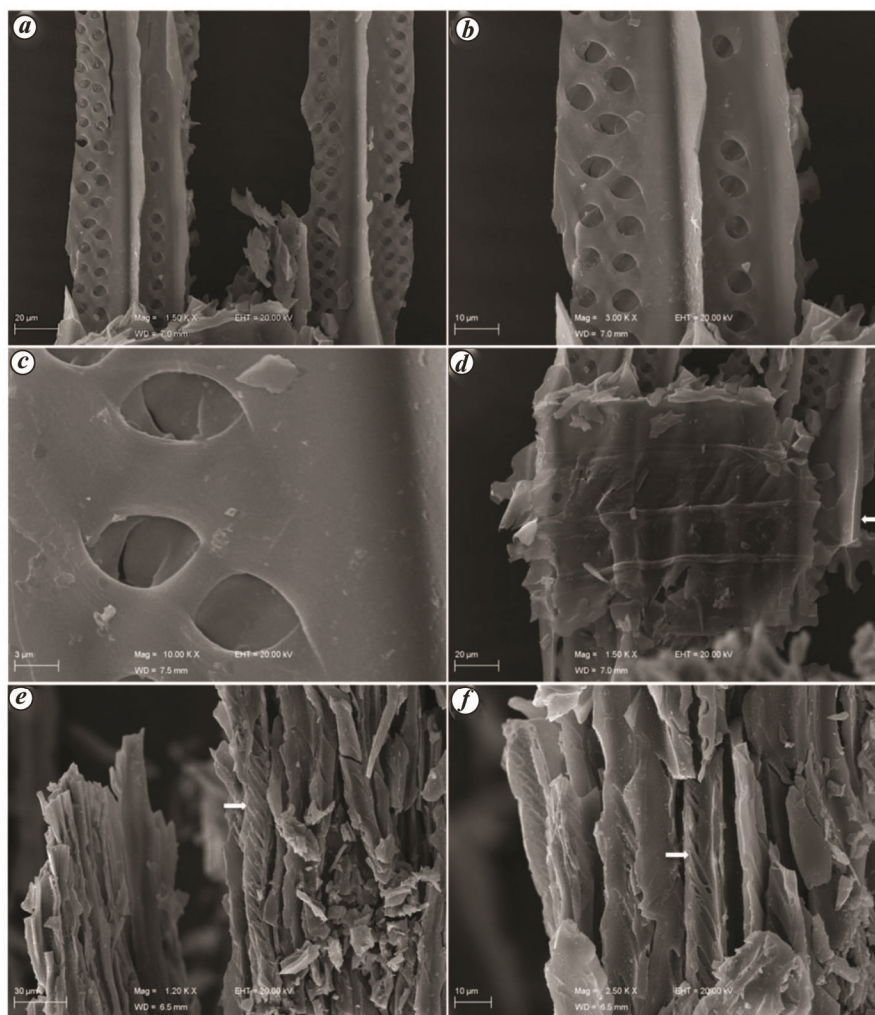
**Figure 1.** *a*, Location map (red circle) of the Saurashtra Basin, Gujarat, India (adapted from ref. 32). *b*, Overview map of the Saurashtra Basin with location of the study site. *c*, Lithological profile of the Than Formation outcrop showing eight deposition levels and the two macro-charcoal-bearing layers.



**Figure 2.** Outcrop of the Than Formation and respective samples of charcoal which were found (\*); macro-charcoal (black arrow). *a–c*, Rock samples of (*a*) level 3-PbUMCN 1298, scale 1.8 cm; (*b*) level 3-PbUMCN 1297, scale 1.5 cm; (*c*) level 6-PbUMCN 1299, scale 3.5 cm.



**Figure 3.** SEM images of macro-charcoal of morphotype 1 in the carbonaceous levels from the Than Formation (Dhran-gadhra Group, Saurashtra Basin) in western India. *a*, Highly fragmented tracheids showing uni- and biseriate pitting; *b*, Fragmented tracheids showing biseriate, alternately arranged pitting and pits with hexagonal borders; *c*, Fragmented tracheids showing triseriate, diagonally arranged pitting; *d*, Pit membrane (white arrow). *a-d*, Pit aperture from circular to elliptical. *e, f*, Uniseriate rays; *g*, Cross-field highly fragmented; *h*, Cross-field with circular to elliptical pits.



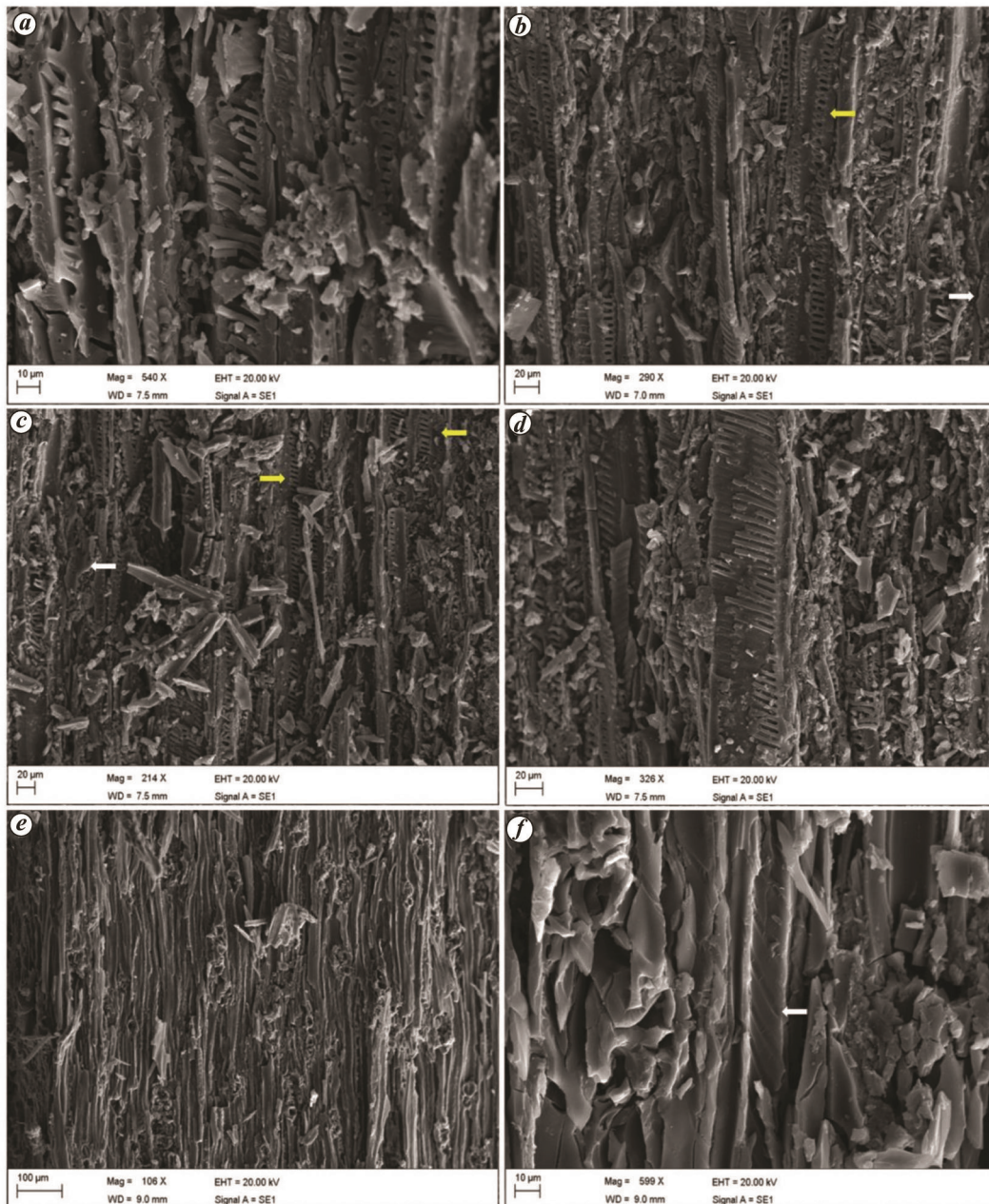
**Figure 4.** SEM images of macro-charcoal of morphotype 2 in the carbonaceous level from Than Formation. *a*, Highly fragmented tracheids showing uni- and biseriate, oppositely to alternately arranged pitting; *b*, Details of (*a*) showing bordered pits; *c*, Details of (*b*) showing elliptical apertures; *d*, Cross-field with four cells in height and showing homogenized cell walls (white arrow); *e*, *f*, Tracheids with ‘checking’ (white arrow).

Morphotype 1 pycnoxylic wood with tracheids varying between 12 and 57  $\mu\text{m}$  in width in radial view, exhibited uni- to triseriate pitting (Figure 3 *a-c*). When bisseriate, pits were alternately arranged (Figure 3 *b*) and diagonally when triseriate (Figure 3 *c*). Pits were circular, 4–6  $\mu\text{m}$  in diameter, to elliptical, 3–8  $\mu\text{m}$  in height and 2–8  $\mu\text{m}$  in width (Figure 3 *a-d*). In some cases, the pits were hexagonally areolate (Figure 3 *b*), while in others a membrane could be observed (Figure 3 *d*). Uniseriate rays, 5–13 cells high, were present (Figure 3 *e* and *f*). Cross-fields, 2–10 cells high (Figure 3 *g* and *h*), exhibiting circular to elliptical pitting could be observed (Figure 3 *h*).

Morphotype 2 pycnoxylic wood with tracheids varying between 22 and 28  $\mu\text{m}$  in width in radial view, exhibited uni- to biseriate pitting (Figure 4 *a*). When biseriate, pits were opposite (Figure 4 *a* and *b*) or alternately arranged (Figure 4 *b* and *c*). Pits were elliptical, 4–6  $\mu\text{m}$  in height

and 5–8  $\mu\text{m}$  in width (Figure 4 *b* and *c*). Cross-fields (rays), four cells in height, without visible pitting were observed (Figure 4 *d*) and tracheids presenting ‘checking’ could be observed (Figure 4 *e* and *f*).

Morphotype 3 pycnoxylic wood with tracheids varying between 28 and 71  $\mu\text{m}$  in width in radial view, exhibited uni- to triseriate and scalariform pitting (Figure 5 *a*). When triseriate, pits were opposite (Figure 5 *a*) and when biseriate, they were opposite or alternately disposed (Figure 5 *b*). Pits varied from elliptical with 1–4  $\mu\text{m}$  in height and 3–9  $\mu\text{m}$  in width (Figure 5 *b*), to scalariform (Figure 5 *c* and *d*). When elliptical, pits could be areolate (Figure 5 *b*). Uniseriate rays, with 2–7 cells in height, were present (Figure 5 *e*). Potential phloem (Figure 5 *b* and *c*) and tracheids exhibiting ‘checking’ could be observed (Figure 5 *f*). Uni- to bisseriate pitting and uniseriate rays are anatomical characters for many modern and extinct



**Figure 5.** SEM images of macro-charcoal of morphotype 3 in the carbonaceous level from the Than Formation. *a*, Overview the macro-charcoal with scalariform pits, showing highly fragmented tracheids, uni- and triseriate oppositely arranged pitting; *b*, Tracheids biseriate, oppositely to alternately arranged pitting with elliptical pits (yellow arrow), and presence of phloem (white arrow); *c*, Tracheids biseriate, oppositely to alternately arranged pitting with scalariform pits (yellow arrow), and presence of phloem (white arrow); *d*, Highly fragmented tracheids with scalariform pits; *e*, Rays in tangential view, 2–7 cells in height; *f*, Tracheid with ‘checking’ (white arrow).

gymnosperms<sup>23,24</sup>. Although cross-field pitting is a taxonomically important feature among conifers<sup>22</sup>, its appearance can be easily distorted during charring<sup>25</sup>. So, the variations observed in the samples related to morphotypes 1 and 2 could be different taxa, or they could be due to distinct ontogenetic stages on the same plant<sup>26</sup>. The presence of uniseriate rays and tracheids with uni- to triseriate scalariform pitting, as observed in morphotype 3, has been described for a range of fossil lignophytes<sup>25–27</sup>.

Within the Early Cretaceous woody taxa, gymnosperm groups like the bennettitales<sup>28</sup> and the cycadales<sup>29</sup> can be considered as a potential source for this morphotype. ‘Checking’ structures are usually generated by cell wall disruption along the S2 layer microfibrils of the cell wall<sup>30</sup>. Such structures were previously interpreted as evidence of pre-charring drying of wood<sup>31</sup>, and could indicate that the source vegetation from which the hypo-autochthonous biomass preserved in the carbonaceous strata

of the Than Formation originated, may have experienced periodical dry intervals. However, more detailed studies including additional field sampling efforts and analysis techniques, are necessary to confirm such an inference. Nevertheless, the presented data confirm the occurrence of palaeo-wildfires in the Early Cretaceous palaeoenvironments which are preserved in the strata now known as the Than Formation, Saurashtra Basin, northwest India. This represents an addition to the global Mesozoic palaeo-wildfire database, confirming that the fire had reached the continental humid ecosystems during the break-up of Gondwana during the Early Cretaceous.

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