# Charcoalified vegetation from the Pennsylvanian of Yorkshire, England: Implications for the interpretation of Carboniferous wildfires.

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## ABSTRACT

New data on some fossil charcoal deposits from the British Isles is integrated into previous studies to provide an indication of our current understanding of the role of fire on land in the Pennsylvanian and also provide strategies for obtaining new information in the future.

The nature and occurrence of fossil charcoal (often called fusain) in sediments and coals (often described as inertinite/fusinite/semi-fusinite) is the main way that the history of Carboniferous fire has been studied. Fires have been shown to have been common in many Carboniferous ecosystems around the world, yet we still have little understanding of the details of what these fires were, where and how they occurred, or their effects upon both on the local ecosystem and the Earth System as a whole. Research has demonstrated that detailed scanning electron microscope studies of charcoal residues can provide data on the plants that have been charred by wildfires.

Information on the amount of charcoal in coal globally appears to relate to atmospheric oxygen composition and this shows that throughout the Carboniferous oxygen levels were as high or higher than those of the present day, suggesting that wildfires were more frequent. Interpreting the frequency of fires in different ecosystems remains fraught with difficulty and calculations within peat (coal) systems are at an early stage. The impact of fire on vegetational change as well as the relationship between fire and climate in the Carboniferous remains little studied.

A study of the inertinite (charcoal) distribution within the Low Barnsley Seam in Yorkshire, England indicates that levels remained high throughout much of the 1.8m thick coal seam. A previous palynological study of the seam has demonstrated three repeated successions of vegetational development interpreted as repeated phases of wet to dry mire development (rheotrophic swamp to ombrotrophic bog). Inertinite peaks above 20% background have indicated a minimum of 18 significant large fire events and an analysis of depositional rates suggests a fire return interval of these large fires to be 500 years or less.

A study of charcoalified vegetation from fine-grained clastic sediments from Swillington Brickworks, Yorkshire recovered from bulk maceration of the sediment, that was not evident from bedding surface examination, has demonstrated that some levels contain abundant leaf charcoal, mainly from pteridosperms, in addition to wood charcoal derived from a range of gymnosperms. The charcoalified plants are interpreted as wildfire residues mainly from surface fires that have been transported and deposited on low-lying floodplains.

Keywords: Pennsylvanian; charcoal; coal; vegetation; wildfire; climate

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## 1. Introduction

Fires are an important part of the Earth System today (Bowman et al., 2009) and as has been previously demonstrated, they represent an important element of the Carboniferous Earth System (Beerling et al., 1998; Scott and Glasspool, 2006; Scott, 2010, 2018; Glasspool et al., 2015).Yet today it is well appreciated that there are a range of fire environments and that some types of vegetation are more flammable than others (Hudspith et al., 2018; Scott et al., 2014; Scott, 2020). There is also an increasing understanding of the relationship between fire and climate change (Scott, 2020). Yet while there is a developing appreciation of fire within the Carboniferous there are several problems that have hardly been articulated, yet alone solved. The questions include the role of fire in the Carboniferous Earth System – from driving aspects of plant evolution to integration into climate models. While the relationship between oxygen and fire occurrence has been widely documented (Scott and Glasspool, 2006; Glasspool and Scott, 2010; Glasspool et al., 2015; Belcher et al., 2013; Berner, 2006; Lenton, 2013; Lenton et al., 2018; Krause et al., 2018) there has been little attempt to integrate these findings into combined atmospheric models and thence to the climate models. There is little understanding of how to document the frequency of fire in deep time and in addition how to link fire events between different environments. How can we, for example, recognise a small fire event that has an impact on one ecosystem rather than a large event that has an impact on several environments? In addition, we lack an appreciation of what plants are being burned and how they may be represented in the fossil record.

Many of these questions are beyond the scope of the current paper but here I wish to address the representation of fire in two distinct environments from a study of charcoal in sediments from the Middle Pennsylvanian of Yorkshire.

Charcoal is a pyrolysis product of wildfire (Glasspool and Scott, 2013). Fire, before the evolution of humans generally started from lightning strikes (Scott et al., 2014). In such a case the lightning causes a rapid increase in temperature that pyrolizes plant material (usually wood) and volatile gases are released, which when mixed with atmospheric oxygen allows combustion to occur (Scott, 2018). This exothermic reaction creates a chain reaction allowing the fire front to spread (see Scott, 2020 for a description of the charcoalification process). The fire may initially spread as a surface fire, but may not only consume surface vegetation but also char litter through the exposure to heat (Scott, 2010). Fire may spread through ladder fuels into the crowns of shrubs and trees but in such cases much of the smaller plant material may be completely consumed by the fire (Scott, 2010). In modern wildfires much of the charred material preserved comes from charred litter that will include all plant organs and even insects (Scott et al., 2000; Scott, 2010). Many modern charcoal assemblages preserve leaves, wood and fertile organs of vascular plants but also mosses and fungi (Scott et al., 2000, 2014).

Taphonomic processes may, however, have a dramatic effect upon the preservation of charcoal assemblages so that wood charcoal may become the most commonly preserved material. However, smaller charcoal fragments may be included in any assemblage but may either be missed or be separated by wind or water and be deposited in a range of settings but may also be missed either through inexperience in the identification of smaller non-wood charcoal, or only found through their bulk maceration of rocks (Scott, 2010). A detailed discussion of charcoal recognition in modern and fossil settings has been previously published (Scott, 2010). It should, however, be noted that the charcoalification process not only increases the carbon content of the plant material but also may re-order the carbon structure (Ascough et al., 2010, 2011). However, exceptional preservation may result from the charcoalification process whereby even delicate glandular hairs may be preserved (Scott et al., 2019) and in decaying leaves fungal hyphae may be preserved (Scott et al., 2000). The charcoal becomes ridged and less compactable so that the three-dimensional features of the plant may be preserved (Scott, 2010). However, in some fossil deposits burial may cause these brittle charcoalified plants to fragment (Scott et al., 2000; Scott, 2010, 2018, 2020).

The relationship between coal and clastic sequences in Carboniferous coal-bearing strata has been debated for over a century. The widespread nature of individual coal seams and the intervals containing clastic sediments led to the idea that a coal seam was synchronous across an area and that a rise in seal level introduced clastic sediment very quickly over the peat forming system as it was so flat lying (Bott and Johnson, 1967; Read, 1969; Ramsbottom et al., 1974). Subsequent sedimentological studies and facies analysis led to the other view that clastic sedimentary environments and peat-forming environments may be found as lateral time equivalents and that migrating environments led to the vertical succession of coal and sediments (Elliott, 1969; Reading, 1970; Scott, 1978).

In more recent years, based mainly on research in the United States of America, emphasis has been placed on the alternation of peat-forming and clastic environments being primarily driven by a changing climate (Cecil, 1990; Cecil et al., 2003, 2014; DiMichele, 2014; DiMichele et al., 2009, 2010). This was based upon research in south-east Asia where it was demonstrated that peats only developed during high rainfall phases and this view has been widely incorporated into both sedimentological and vegetational models (Cecil, 1990; Cecil et al., 2003). In addition, the driving mechanism of climate change and hence sea level change has led to further models of sequence stratigraphy where peat formation occurs during different phases of the climate cycles (Eros et al., 2012). Yet if this is the case then the implications for our understanding of fire systems is fundamental. Several consequences and questions arise from this interpretation. The first is that a fire within a mire system, while potentially being widespread, would not spread to non-peat forming vegetation as the two types are not coeval. The reverse situation would also be true. Secondly the frequency of fires within the peat-forming environments could be significantly different from fires in non peat-forming environments. Thirdly, the varied nature of non peat-forming vegetation may provide different fire characteristics from the peat-forming vegetation. This also has implications as to what charred plants may be found in each sedimentological setting. While the significance of Carboniferous fires was highlighted more than 30 years ago (Scott, 1989, Scott and Jones, 1994) we have made relatively little progress in that time in trying to resolve many of these issues.

Another pressing issue concerning Carboniferous fire systems is the role of changing oxygen composition of the atmosphere through that Period. Geochemical models of atmospheric oxygen through the geological record suggested that levels rose through the late Devonian reaching above modern levels (21%) in the Carboniferous (See Bergman et al., 2004; Berner et al., 2003; Berner, 2006; Lenton, 2013; Lenton et al., 2018) thus having an impact on the nature of Carboniferous fire systems (Scott and Glasspool 2006; Glasspool et al., 2015). The increasing occurrence of charcoal from the late Devonian into the early Carboniferous suggests that this rise in atmospheric oxygen indeed had a significant impact on wildfire systems (Rimmer et al., 2015). Experimental work on fire ignition and spread indicates that rising oxygen levels increase the number and intensity of fires allowing wetter plants to burn (Watson and Lovelock, 2013; Lenton, 2013;  Belcher et al., 2013). However, oxygen curves produced by biochemical modelling may differ considerably in both how they are produced and the results they generate. Unlike with carbon dioxide there are no proven palaeo-proxies for atmospheric oxygen. One attempt was to use the data derived from the quantity of charcoal in peat/coal over geological time (Glasspool and Scott, 2010). This is based upon the observation that peats form in ever-wet conditions and in today's world where the $O_2$ concentration is 21% global charcoal in peat data gives an average around 4%. It is also based upon the experimental data that shows few fires will start and spread when $O_2$ levels are below 17% and that more fires will burn, both wetter plants and producing hotter fire over 23% and are unlikely to have been sustainable because of fuel limitations above 30%. New calculations suggest that Carboniferous oxygen levels remained above the present 21% throughout the Carboniferous thereby having a significant impact upon the Earth System (Glasspool et al., 2015).

Other recent research on the Carboniferous climate and indeed on its relationship to carbon dioxide ($CO_2$) levels in the atmosphere has further allowed a much more subtle interpretation to be established (Montañez and Poulsen, 2013), which in turn may have had an input on the nature of Carboniferous fire systems. The inter-relationships of climate forcing and fire in the Earth system has only been established in recent years (Bowman et al., 2009). In this paper the authors demonstrated both positive and negative effects of wildfire on climate including the production of $CO_2$ in to the atmosphere that will increase warming at least in the short term and soot that may be deposited upon snow that will have an impact upon albedo, again increasing warming and also the burial of charcoal that may in the long term reduce $CO_2$ and hence having cooling effect. No current Carboniferous climate models take any account of fire in the Earth System despite the need highlighted by Beerling et al. (1998).

In addition, there has been significant progress in our understanding of the nature of both modern fire systems as well as the significance of post-fire erosion (Moody and Martin, 2001, 2009; Cerda and Robichaud, 2009; Scott, 2020). All these data make a reassessment of Carboniferous fire systems timely as significant new questions can now be asked and some data provides significant new insights. In particular we can ask several questions and some of these lead to new avenues of research that should lead to progress in our future understanding of Carboniferous wildfires. By the Carboniferous we have the three main elements needed for fire (Scott et al., 2014): 1. Fuel: plants have spread widely on Earth to many different habitats and were able to provide a substantial fuel load. 2. An ignition source: lightning would be the primary ignition source (although volcanic eruptions and sparks from rock falls would provide another source). 3. Oxygen: as we have seen the atmospheric levels of oxygen according to all authors would have been sufficient to sustain fire throughout the Carboniferous.

We need to ask in particular:

- What was being burned?
- What kind of fires were there?

- Were any types of vegetation more fire prone?
- Can we identify different fire regimes?
- Can we assess fire size and frequency?

In this paper I examine two examples from the Pennyslvanian of Yorkshire, England, that allows us to address some of these issues.

## 2. Material and Methods

### 2.1. Coal.

A 288-cm length of core through the Low Barnsley Seam (Westphalian B) was taken from St Aidans Opencast Mine, SW of Leeds, Yorkshire, England (NGR SE 40 28) (Figure 1) was made available for study by British Coal. At this locality the seam is composite comprising three leaves of coal (Bottom, Middle and Top) and a thin 'Special Category' coal (too thin to be economic) between the Bottom and Middle leaves (Bartram, 1987a,b). The total thickness of the coal was 1.8 m.

### 2.1.1. Preparation and study.

The core was embedded in resin and polished bocks were prepared representing the complete length of the seam. Macerals were counted for each centimetre unit throughout the seam. Details may be found in Bartram (1987a,b) (The original main data sets from Bartram (1987a) may be seen in the Supplementary Publication).

### 2.2. Clastic sequence.

Middle Coal Measures between the Clay-Cross Marine Band and the Two Foot Marine Band (Westphalian B/Duckmantian/Moscovian)) were examined at Swillington, Yorkshire, England (NGR: SE 385315) (Figure 1) that exposes strata from the middle of the Thornhill Rock to above the Lidget Coal. The Swillington brickpit, east of Leeds, exposed a large 200m long cut that has been worked since 1973 (Scott, 1978, Plate 26; Scott, 1984, Plate 1) and the section has been studied for more than 30 years in various different stages. In 1976 there was a stepped section from the top unit of the Thornhill rock to just above the Lidget Coal (Figure 2) that was recorded in Scott (1978). The photo of the section was taken in the early 1990s (Figure 2a). The bottom half of the quarry consists of two upward-coarsening units (beds 2-9: containing non-marine bivalves in the shales and ironstones and coarsening to a sandstone separated by a thin coal). A thin persistent coal (bed 10) caps the upper unit and a very variable sandstone/silty sandstone unit succeeds (bed 11). The remainder of the section consists of coals, seat-earths and siltstones (beds 12-23) with another thin mussel band at the top of the quarry (bed 24). Some plant fossils from this quarry have been described elsewhere (Scott, 1974, 1978, 1984; Scott and Chaloner, 1983; Scott, 2018). The Bed 20f is composed of alternations of medium and dark grey plant-rich and coaly horizons, first reported by Scott (1978). Some of the material reported here came from the original sampling (1972-1976) but additional samples were collected through the 1980s and early 1990s.

### *2.2.1. Preparation and study*

Bulk samples (from 100g to 500g) of each layer were dissolved in HF and sieved for meso-fossils (Pearson and Scott, 1999; Glasspool and Scott, 2013). Picked specimens were examined under the scanning electron microscope, originally using a Cambridge S600 (Scott and Collinson, 1978) but in more recent years using a Hitachi S2400 SEM (Scott, 2010). Samples were gold or carbon coated. All specimens will be deposited in the Palaeobotanical Collections of the Natural History Museum London upon the completion of the current studies.

## 3. Results

### *3.1 Charcoal in Coal*

The Low Barnsley seam from the St. Aidans core was studied by Kate Bartram as part of a PhD investigation and the data presented here was a result of her research under the author's supervision (Batram, 1987a). The data is presented in full both in the unpublished thesis and the critical data is also presented here in supplementary data tables. The petrographic results included both maceral and microlithotype analysis, the latter presented in Bartram (1987b). In this report only the distribution of the inertinite macerals are presented.

Most of the inertinite present was fusinite and semi-fusinite. The distribution of the inertinite fraction of the coal macerals is shown in Figure 3. What is clear is in all three main leaves of the coal that inertinite is consistently above 10% throughout the seam and generally greater than 20%. In order to interpret a major fire event rather than simply background fire a Figure of 20% was used as a baseline to allow for the identification of peaks above a background level. In this analysis five major peaks were found in the lowest leaf of the coal, four major peaks in the middle part of the coal and eight major peaks in the upper part of the coal (Figure 3).

One aspect that was not recorded by Bartram (1987a) was the sizes of the inertinite particles but the polished blocks are no longer available for re-study as they were lost in the move from Chelsea College to Royal Holloway College (University of London) in 1985.

### *3.2 Charcoal in terrestrial clastic sediments*

There are several factors that make the identification of charcoalified foliage difficult. Wildfire creates conditions whereby many leaves of living plants are completely combusted during the fire (Scott, 2010). This can be seen after a fire has passed through vegetation. Leaves have been burned whereas trunks, stems and branches of woody plants may be only partially destroyed (see illustrations in Scott, 2010; Scott et al., 2000). Many of the charred leaves in charcoal residues following a wildfire have been derived from the pyrolysis of the leaf litter as the flames of the wildfire have passed. In such cases leaf material will range from being completely charred (at a range of temperatures and for a range of times) to being partially charred to some being un-charred. Taphonomic processes may also affect the charcoalified plants (all plant organs, fungi and even insects). This includes transport by wind and water where different plant organs charred at different temperatures may be sorted (Nichols et al., 2000). The charring temperature may also cause shrinkage that is temperature dependant. It has been shown experimentally with both wood and fertile structures that the dimensions may be reduced up to 50% during the charring process (Lupia, 1995; Osterkamp et al., 2018). In addition, the fragility of charred leaves and fertile structures in particular may mean being broken both before and after burial in the sediment. Given the above clearly the dimensions of charred and un-charred specimens of the same plant may differ and together with fragmentation issues may make definitive identification difficult. The charring process may, however, preserve structures that may be rarely preserved in normal compression material. For example small glandular hairs on a range of plant organs may be preserved and three-dimensional images (see Scott et al., 2019 for an example) may be obtained. It is quite possible for glandular hairs/papillae on leaves to be more easily preserved and imaged. This has been shown for leaf and fertile material from a range of ages (e.g. Carboniferous – Scott, 2010; Scott et al., 2019; Cretaceous - Herendeen et al., 1999; Brown et al., 2012).

Compression plant assemblages have been recorded by Scott (1976, 1978, 1984) from many of the beds at Swillington. These are readily identified from both compression fossils on bedding surfaces of shales and siltstones and also in ironstone nodules. Within Bed 20f (Figure 2) the compression plant material was very fragmented and not easy to identify. Charred versus un-charred plant material can be most easily distinguished using dark-field microscopy using a low powered microscope with the specimens under water in a petri-dish (see Scott et al., 2017 for an example). The taxa from this bed were recorded in Scott (1978 – Table 1).

Within a range of facies the following taxa of compression fossils were recorded by Scott (1976, 1984) (revised names are not given as the specimens have not been re-studied): Lycopsids: *Lepidodendron ophiurus* Brongniart, *Lepidodendron mannabachense* Presl, *Lepidodendron* sp. *Lepidostrobus ornatus* Brongniart, *Lepidostrobus hibbertianus* Binney, *Lepidostrobus* sp. *Lepidostrobophyllum lanceolatum* (Lindley and Hutton) Bell, *Sigillari*a sp., *Sigillariostrobus* sp., *Lepidocarpon* sp., *Bothrodendron* sp. leafy shoots, *Stigmaria ficoides* (Sternberg) Brongniart, *Cyperites bicarinatus* Lindley and Hutton, Sphenopsids: *Calamites* spp. including *Calamites cistii* Brongniart, *Calamites suckowi* Brongniart, *Calamites undulatus* Sternberg, *Calamites carinatus* Sternberg, *Calamostachys* sp., *Annularia radiata* (Brongniart) Sternberg, *A. sphenophylloides* (Zenker) Gutbier, *Asterophyllites grandis* Sternberg, *Asterophyllites equisetiformis* Brongniart, *Asterophyllites charaeformis* (Sternberg) Unger, *Pinnularia* sp. *Sphenophyllum majus* (Bronn) Bronn, *Sphenophyllum trichomatosum* Stur, *Sphenophyllum cuneifolium* (Sternberg) Zeiller, *Sphenophyllum myriophyllum* Crepin, *Laveineopteris loshii* (Brongniart) Cleal et al., *Neuropteris obliqua* (Brongniart) Zeiller; *Laveineopteris tenuifolia* (Schlotheim ex Sternberg) Cleal et al., *Paripteris pseudogigantea* (Potonié) Josten*, Alethopteris decurrens* (Artis) Zeiller, *Alethopteris lonchitica* auct, *Karinopteris daviesii* (Kidston) Boersma, *Mariopteris nervosa* (Brongniart) Zeiller, *Mariopteris muricata* (Brongniart) Zeiller, *Sphenopteris footneri* Marrat, *Eusphenopteris.* cf. *obtusiloba* (Brongniart) Novik, *Renaultia gracilis* (Brongniart) Zeiller, *Palmatopteris furcata* (Brongniart) Potonié, *Zeilleria denticulata* (Sternberg) Kidston, *Zeilleria hymenophylloides* Kidston, *Zeilleria.*sp., *Pecopteris plumosa* (Artis) Brongniart, *Lobatopteris miltoni* (Artis) Wagner, pteridosperm axes; Cordaites: *Cordaites principalis* (Germar) Geinitz, *Cordaites* sp. *Cordaicarpus* sp., *Artisia approximata* Lindley and Hutton.

Within Bed 20f (Figure 2b) compression taxa identified included: Flattened trunks of *Siglilaria* sp., *Lepidodendron* sp., *Calamites* sp. *Neuropteris* spp (sl), *Alethopteris* spp., *Calamites* sp.*,* *Calamostachys* sp., *Annularia* sp., *Lepidophloios* sp., ?*Cordaites* sp., *Sphenopteris* spp. (sl), Pteridosperm stems. Arthropod cuticles were also recovered.

Quantification of the charcoal is difficult as many of the specimens fragment during processing so that quantification means little (see Scott et al., 2017 for a discussion of the general issue; Lancelotti et al., 2010) as does the nature of the vegetation (Hudspith et al., 2018). However, general comments on abundance is made.

### *3.2.1 Descriptions of charcoalified taxa*

#### *3.2.1.1 Lycophytes*

Details and descriptions referring to Plate I. Specimens: SW20f9-18a, SW20f3b

Lycopsid material is relatively rare. Most of the charred lycopsid material represents possible isolated leaf cushions (Plate I). These leaf cushions are long and narrow (Plate I, 1) but preserve stomata on the leaf cushion surface (Plate I, 3,4). Another possible leaf cushion fragment (Plate I,  2) shows what appear to be papillae (Plate I, 5) but also have *Lycospora* spores adhering to the cushion (Plate I, 6). These leaf cushions appear to be charred on the outside and sloughed off the trunk much like bark scales on charred modern conifer trunks (Scott, 2010)

#### *3.2.1.2. Sphenophytes*

Details and descriptions referring to Plate II. Specimens: SW13; Bed SW20f9-15a

Only one example of a charred *Calamites* stem was found at Swillington (Plate II, 1). The illustrated specimen shows typical features of a *Calamites* pith cast but the fragility of the specimen made undertaking detailed SEM observations difficult.  Fragments of charred *Asterophyllites* foliage appears to be relatively rare (Plate II, 2-4). One specimen is illustrated by both light microscopy (Plate II, 2) and by SEM (Plate II, 3,4.) Typically the leaves occur in whorls and the stomata are relatively simple (Plate II,  4).

### *3.2.1.3. Ferns and Pteridosperms*

Ferns and pteridosperms that are widely represented in plant compression assemblages from all Pennsylvanian compression assemblages (Bashforth et al., 2016a,b; Šimůnek, 2004) and in the Swillington Bed 20f are represented by a large range of charred pinnules. Such material makes up more than 80% of the charcoal assemblage. There are numerous genera and species represented but for the most part these cannot be securely identified. The number of different types indicate a considerable diversity.

*Alethopteris* spp. Specimens SW20f19d, SW20f2-e, SW20f18b, SW20f19a. (Plate III, 1-5).

Rare pinnule fragments show a range of morphologies but they are very fragmented and their stomata are not well preserved. The pinnules show typical alethopterid venation and their sizes and vein density indicates that they may belong to more than one species, with the specimen illustrated (Plate III, 1-3) possibly belonging to narrower pinnule form such as *A. decurrens.* The specimen illustrated on Plate III, 4,5 has a much wider pinnule, more typical of *A. lonchitica*. Stomata ((Plate III, 5) are difficult to discern.  Both these species occur in the compression flora.

*Neuropteris* sp. sl. Specimen SW20f24f (Plate III Figure 8,9).

Only one possible fragment of a neuropterid pinnule was found in the charred assemblage (Plate III, 8,9). However, as the tip of the pinnule only was found secure identification is not possible. The specimen had a rounded pinnule. The sunken stomata have several subsidiary cells and many of the epidermal cells are papillate. However, there may also be some hairs on the under surface but these are difficulty to see in detail as they are mainly broken.

?*Mariopteris* sp. (Plate V, 3) Bed SW20f9 (specimen lost)

Only one possible mariopterid pinnule was found in the assemblage (Plate V, 3) but the specimen was not well enough preserved to see the full leaf shape or the epidermal detail.

Pteridosperm foliage fragment. Specimen 20f2-1 (Plate III, 10,11)
Pinnule fragment with forking veins derived from pinnule base. Simple stomata with smooth epidermal cells.

*Sphenopteris* spp. (Plates IV, V, VI)

This group of specimens may make up more than 80% of the charcoalified pinnule assemblage. Several different types were found but none preserved enough features to allow specific (or even generic) identification. Here I describe them under types.

Type 1. Specimen SW20f4a. (Plate IV, 1,2). Fragment of large lobed pinnule with indistinct venation. Dense simple stomata (Plate IV, 2) without papillae on the leaf surface.

Type 2. Specimens SW20f19acx; SW20f6a (Plate IV, Figures 3-6).. Frond fragments with incomplete pinnules. Hair bases visible on rachis (Plate IV, 3) and rarely on central pinnule vein (Plate IV, 3). Large vein derived from pinnule base with smaller dichotomous veins. Stomataliferous surfaces with papillate epidermal cells and sunken stomata with overarching papillae (Plate IV, 4).

Type 3. Specimen SW20f23g. (Plate V, 1,2). Highly lobed pinnule with papillate epidermal cells on stomataliferous surface with indistinct venation. Small sunken indistinct stomata with papillate subsidiary cells (Plate V, 2).

Type 4. Bed SW20f9 (specimen lost). (Plate V, 4,5). Indistinctly lobed pinnule with large guard cells surrounding sunken stomata (Plate V, 5). Pinnule shape reminiscent of *Eusphenopteris* sp.

Type 5. Specimens SW20f17e (Plate V, 6-8). Specimen SW20f24c (Plate VI, 1-3). Lobed pinnule (Plate VI, 1) with dichotomous veins derived from central mid-vein that show scarce hair bases (Plate VI, 2; Plate V, 7). Folded oval pinnule with thick veins derived from pinnule base (Plate V, 6). Papillae both on veins and on epidermal cells (Plate V, 7,8). Sunken stomata with papillate subsidiary cells (Plate V, 8).

Type 6. Specimen SW20f4D. (Plate VI, 4). Highly lobed pinnule with strong venation. (Plate VI, 4)

Type 7. Specimen SW20f17e (Plate VI, 5,6). Lobed pinnule with distinctive mid-vein and single veins emerging which dichotomises. Fungal hyphae visible on leaf surface. Stomata simple with random orientation. No papillae.

Spiny axes, stems and hooks (Plate III, 6, 7; Plate VII)

Type 1. Specimen SW20f32d.Thin axes with long narrow spines, up to 200µm long (Plate III, 7).

Type 2. Specimen SW20f28j. Isolated curved spines, 1mm long (Plate III, 6).

Type 3. (Plate VII). Specimen (Bed SW20f9; unnumbered, lost – Plate VII, 1). Specimen SW20f27c (Plate VII, 2) Specimen SW20f6b. (Plate VII, 3,4) Specimen SW20f27a (Plate VII, 5). Specimen SW20f27b (Plate VII, 6,7). Broad axes ranging in width from 1mm to 1cm and several centimetres in length. Scattered squat spines, less than 500µm high and up to 250µm wide at base with a distinctive cellular structure visible on broken spines (Plate VII, 4). Simple epidermal cell pattern comprising rows of elongate rectangular cells 20µm long (Plate VII, 7).

Pteridosperm xylem (Plate VIII). Specimen SW20f14b. Fragile and highly fragmented charred axis. Tracheids easily crushed and separate (Plate VIII, 1). Tracheids with multiseriate pitting (Plate VIII, 2,3). Such wood with multi-seriate pits is found commonly within the pteridosperms.

### *3.2.1.4. Cordaites and ?conifers.* (Plates IX-Plate XI)

Wood (Plate IX). Bed SW20f9; Specimen SWf1; SW20f9-14c

The problems of identifying such material has been discussed by Clack et al. (2019). Uncrushed woody fragments of *Dadoxylon* type occur within the charcoalified assemblage but make up less that 5% of the charred material. The tracheids may show both single and double rows of bordered pits. Bordered pits are also present on ray cells. The fragility of the specimens means that obtaining good sections in different planes needed for further description and identification is difficult.

Cordaite-like wood. SW20f21c.(Plate X, 9, 10). Other gymnospermous wood (?Cordaite/*Dadoxylon*-type) shows 3 rows of bordered pits.

?*Cordaites* leaves (Plate X) Bed SW20F9. Specimens SW20f25f, SW20f25c, SW20f13a
Blade-like leaf fragments occur as 5% of the charcoal assemblage. These show features that are similar to specimens described and identified as *Cordaites* (Šimůnek, 2007b, 2018, 2019; Šimůnek and Florjan, 2013) but differ in other aspects. The comparison of dimensions of charred and

uncharred material may be made more difficult as shrinkage up to 50% may have occurred during the charcoalification process.

Type 1 leaf fragments contain multiple parallel rows of stomata. These stomata are slightly sunken and two large subsidiary cells are prominent but in places two additional subsidiary cells may be present. However the detail may be obscured as there are dense areas with epidermal cells with papillae. These papillae (up to 20µm in diameter) appear to have expanded peltate tops (Plate X, 4, 8). Sometimes these papillae (or even short hairs?) have collapsed or have been severed off (Plate X, 3, 8). A folded specimen seems to show that the upper and lower surface of the leaf is different with a non-stomatiferous surface with elongate epidermal cells which had small flatter papillae (Plate X, 7).

Type 2 leaf fragments (Plate X, 5,6) show rows of stomata witch four subsidiary cells. Epidermal cells do not have papillae. Folding of the leaf before charcoalification makes further description difficult.

?Conifer leaves (Plate XI): *Swillingtonia denticulata* Scott and Chaloner.
Original specimens from SW20f9 described by Scott and Chaloner (1983) and deposited in the Natural History Museum, London. Specimen NHM V61025 (Plate XI, 2). Specimen SW20f5a (Plate XI, 3,4).

*Swillingtonia* leafy shoot. Bed SW20f9 . Specimen illustrated by Scott (1974) but now lost. Specimen, 5mm long, shows lanceolate spirally arranged leaves (Plate XI,1). The leaves have decurrent bases and bear stomata only on the abaxial leaf surface. Isolated leaves (1-5 mm long) (Plate XI, 2-4) are narrowly triangular (some described in the original material are forked) and have a distinctive midrib with two broad stomatal bands up to 6 or 7 stomata wide on the lower surface of the leaves. The stomata (15µm x 20µm) are sunken with two guard cells and two distinctive bean-shaped subsidiary cells. Stomata of adjacent rows tend to be alternate (Plate XI, 2). Stomata share encircling cells. The midrib comprises elongated epidermal cells and rounded cells, each with a papilla. The leaf margin is denticulate. No stomata are present on the upper surface. Here there are two types of cell: predominantly elongate cells and a lesser number of rounded papillate cells. (Plate XI, 4).

*Comments*: *Swillingtonia* was considered by Scott (1974) and Scott and Chaloner (1983) as a conifer. They rejected a lycopod origin for the material and provided detailed arguments for a coniferous origin. Subsequently Hübers et al. (2011) have rejected a conifer origin, preferring a lycopsid origin. However, the material studied by Hübers et al. (2011) was only of fragmentary cuticles and not well-preserved leaves or leafy shoots. Until more definitive material is obtained the idea that this material is coniferous is still valid. Other Moscovian age conifer leafy shoots and dispersed charcoalified leaves have been described by Scott et al. (2010) from North America and are similar to charcoalified coniferous material from Garnett and Hamilton also in the USA (Winston, 1984, Rothwell et al., 1997; - see also Looy 20013 for a discussion of fire and early conifers).The material is relatively rare in the Swillington assemblages and the identification may be considered problematic until more material is discovered.

### *3.2.2 Comparisons of charcoalified and non-charcoalified plants*

A list of all the compression taxa obtained from Swillington has been given in an earlier section. However, comparisons of the complete flora from Swillington with the charred assemblage are not easy. This is because of several factors. The first is that specific identification of the charcoalified taxa is in most cases not possible. In most cases also plant assemblages have been transported and few *in situ* plant assemblages were recovered (Scott 1976, 1978, 1984). The charred assemblage is likely to have been charred and transported to a depositional site. Scott (1978, 1979) identified a number of distinct plant communities, some dominated by lycopsids, others by sphenopsids and others by pteridosperms. The charred assemblage is dominated by pteridosperm leaves. However, this may reflect both original ecology as well as taphonomy. The charred assemblage is most likely to have been derived from the charring of plant surface litter (see Scott, 2010 for a discussion) but transport of different plant organs that have been charred at different temperatures are likely to have resulted in a taphonomic separation (Nichols et al., 2000). A broad comparison, however, of the charred and non-charred assemblages within the river floodplain sediments seems to indicate that a diverse pteridosperm-dominated plant assemblage was charred, that itself was living on a flood plain and that the transport of the material from the original fire site may have been minimal.

## 4. Discussion

### *4.1 Wildfire in peat-forming systems*

The abundance of charcoal (fusain) in coal (e.g. Uglik and Nowak, 2015) has proven of major significance not only to our understanding of wildfire in the Carboniferous but also in the debate of the significance of atmospheric oxygen in the late Paleozoic (Glasspool and Scott, 2010; Glasspool et al., 2015). While it is now widely accepted that Pennsylvanian peats contain evidence of wildfire from the abundance of charcoal within them and that this abundance may be a result of elevated atmospheric oxygen (Glasspool and Scott, 2010; Lenton et al., 2018; Krause et al., 2018), our understanding of the nature of these fires has not been widely developed. One area of promise is to study the nature of charred plants within coal balls in North America, especially where there is significant vertical representation (Scott, 2000, 2010) but even this approach is unlikely to give us all the answers.

The way in which Carboniferous coals are generally studied provides us with significant challenges with regard to the interpretation of the wildfire system. Coals are generally collected as increments within a coal, that is either as discrete units, such as 5, 10 or 20 cm units (e.g. Scott and King, 1981; Bartram, 1987a,b) or as benches, as is common in the USA (e.g. Eble and Greb, 2016; Eble et al., 2019). In addition, coals collected in this manner may be subsequently crushed and mixed to get a good representation of the coal layer (e.g. Eble et al., 2019). In this way there will be significant data loss concerning wildfire history. Firstly there may be evidence of more than one fire within the sampled unit and secondly the potential of identifying the plants that are preserved as charcoal (fusinite/semifusinite/inertinite) is likely to have been lost.

One aspect that needs to be considered is the problem of the relationship between the identification of charcoal formed by wildfire and inertinite macerals found in coal and identified in reflectance in polished blocks. While the majority of the inertinite macerals such as fusinite, semi-fusinite and inertodetrinite are widely accepted as belonging to charcoal (Scott, 2002; Scott and Glasspool, 2006) others such as macrinite, micrinite and secretinite may have other origins (see discussion in Hower et al., 2009; O'Keefe et al., 2013; Scott and Collinson, 2020). However, the percentage of these types with respect to the main intertinite macerals are usually relatively small and given the high levels of the main macerals in most Carboniferous coals this would make little difference in trying to identify fire events. There is no persuasive evidence of the bulk of inertinite macerals being formed naturally by a simple dry 'oxidation' process rather that being a result of wildfire (Scott and Glasspool, 2006).

If fire is particularly significant within the Carboniferous peat-forming systems how can they be studied? In more modern systems continuous peat cores are made and fire events are distinguished as being peaks of charcoal above a background level (Power et al., 2006; Feurdean et al., 2020). This raises several issues. First is that continuous coal sampling is necessary to adequately identify fire events and hence have any chance of interpreting fire frequency. This problem has been discussed by Hudspith et al. (2012). The second is the identification of the charred plants. Many organs may be larger than the area imaged and indeed also the nature of peats and the fragility of charcoal may mean that specimens are crushed and fragmented leading to more difficult identification. This problem within a Paleocene coal has been discussed by Steart et al. (2007; Collinson et al., 2007; see also Scott, 2010).

Studies of Yorkshire Middle Pennsylvanian (Duckmantian/basal Moscovian) coals have produced some insights into the fire systems within the mire ecosystem.

In her study of Moscovian coals from Yorkshire, Bartram (1987a,b) undertook detailed continuous sampling of uncrushed coals that linked petrography to palynology (see Supplementary publication). She demonstrated that the peats showed changing vegetational types during the development of the seams (Bartram, 19987b). What these polished blocks provided was the ability to record the vertical occurrence of inertinite (fusinite/semifusinite/inertodetrinite) macerals in more detail. Such data has been previously published (Scott, 2000) but here we can consider the implication of the data in more detail (Figure 3). As we have indicated the identification of fire events requires peaks above background to be used. However, in contrast to modern peats where charcoal contents are relatively low and peaks above background are high in the Carboniferous example background levels are high. This may mean that frequent smaller fires are represented by the background and the peaks represent larger, more significant fire events. Within the Barnsley seam example (Figure 3) we can use a threshold of 20% inertinite as background and peaks above 20% to represent significant fire events. This is however likely to be an underestimate. Within the seam totalling about 1.8m there are 18 events with inertinite peaks > 20%. Using 15% as a baseline fire events merge and an analysis using 10% inertinite threshold provides little fire event resolution. We should note also that the major events occur with more frequency in the vegetation types (all dominated by lycopsids) in the relatively less wet phases of peat development but there is no secure linkages between fire and vegetation phase.

Is it possible to use this data to interpret fire frequency? If we were to take a simplistic approach we would identify an average peak interval of 10cm. If we were to take a simple calculation of 10cm coal approximates to 100 cm of peat and that the peat formed at approximately 2mm/year then this would equate to a large fire every 500 years (Scott and Stephens, 2015) (18 fire events in 1.8m coal). However, this figure may be misleading, as there is an indication that small fires at least would have occurred at a much greater frequency. It is clear that a more detailed analysis would be needed to give a more precise figure but we need more comparative data. It is possible that distinguishing peaks dominated by different sizes of inertinites and indeed different categories of inertinite may provide additional data (see Hudspith et al., 2012 for a discussion) as in modern peat systems fires may occur in sub-tropical environments from 200 – 700 year intervals. In their study of Permian coals intervals were shown to vary considerably within a coal seam. In addition, it has been shown that different peat types may compact in different ways and that a simple de-compaction ratio of 10:1 may be insufficient (Scott and Stephens, 2015). Given all the complexity it is suffice to say we still have much to learn about the frequency of the fires in these Pennsylvanian peat-forming systems but their impact should not be ignored.

We can, however, make a few observations based upon what we know of the structure and ecology of the vegetation living in these peat-forming systems (DiMichele and Phillips, 1994) (Figure 4). There has been extensive studies on not only the growth and stature of the Carboniferous lycopsids but also on their ecological requirements (DiMichele, 1980, 1983, 1985, 2014; DiMichele and Bateman, 1992, 2020; Phillips, 1979, Phillips and DiMichele, 1992; Dimichele and Phillips, 1985, 1996; DiMichele et al., 2013; Boyce and DiMichele, 2016; Thomas, 1978; Opluštil et al., 2010) We know, therefore, that the vegetation of the Low Barnsley Seam is dominated by wet-loving lycopsids. The dominance of different lycopsids change as the peat develops. What is less clear is how wet the surface peat layers were and how easily they may have dried out and hence if the surface vegetation was susceptible to fire. There are several implications for fire events given the nature of the vegetation. Most fire events today start with surface fires and these may spread to the crowns of the tree through ladder fuels (Scott, 2020). Yet the nature of the arborescent lycopsids in particular may hinder such a spread. This is because as many of these arborescent lycopsids grow their leaves are shed and the trunk is photosynthetic (Thomas, 1978; DiMichele and Bateman, 1992, 2020). If the trees in an area grew at different rates then this may provide a route for fire spread as would be the occurrence of downed trees. However, we may be seeing several distinctive types of fire depending on the dominance of the particular genus or species of plant (Figure 5). If we are dealing with a drier raised bog dominated by smaller lycopsids such as *Chaloneria* then the fires may essentially surface fires. We should not discount the possibility that some of the peat itself may be burned by ground fires (Hadden et al., 2013; Huang and Rein, 2016). However, where there are areas of tall lycopsids such as *Lepidodendron* SL then the fires may start by lightning strikes in the leafy crowns of the trees and spread between the dense crowns (Figure 5). There would be no occurrence of a surface fire in this case.

In such a system much of the smaller charcoal particles would be lofted in the wind and be widely distributed perhaps as inertodetrinite. The lycopsids themselves have little secondary wood and identifying charred crushed periderm may be difficult in polished blocks and fragment through coal maceration to release the charcoal. As a consequence of these observations it is clear that we have some way to go to begin to understand the nature of the fires in the peat-forming system. Data from another Yorkshire Moscovian coal suggests that peat formation may cease following a catastrophic fire event (Scott, 1978, 2000; Scott and Jones, 1994).

An important additional issue is vegetational heterogeneity and the interconnection between different communities. We should note here that fires usually start as surface fires and develop into crown fires usually via ladder fuels (Figure 4, see Scott, 2020). It has been shown in several studies that many Pennsylvanian coals are not only heterogenous vertically but also laterally (Gastaldo et al., 2004; DiMichele et al., 2002, 2007; DiMichele and Phillips, 1988) and that there may be a diversity of life form within small areas (Bek et al., 2015) that may be affected by not only flood events (Pocknall et al., 2020) but also by fire events. In very wet peat-forming systems (swamps) fire spread may be hindered as surface fires unless there is a significant drying of the surface vegetation/litter. If the fire spread was predominantly via the crowns of trees (Figures 4, 5) then the uniformity/ patchiness of the vegetation may prove significant. Large areas of monotypic vegetation with single aged stands may be more susceptible to fire than very diverse patchy communities of different life forms of different age characteristics. In tropical rain forests today fire may affect one or two trees but not spread (Cochrane, 2009 ; Scott et al., 2014; Scott, 2018). It must, therefore, be considered that frequent small fires may increase vegetational heterogeneity and hence ecosystem survival and also this would have an impact on the distribution of charcoal within coal seams. Our increasing recent understanding of vegetational structure within Carboniferous coal seams should help us make some predictions on the potential spread of fire in such ecosystems.

### *4.2 Wildfire in non-peat-forming systems*

Fossil charcoal was first discovered in the clastic sequences at Swillington in the early 1970s and the first plant occurring as charcoal described was an early conifer (Scott 1974) later described as *Swillingtonia* (Scott and Chaloner 1983) that was represented by leafy shoots and small leaves. While this designation has been accepted by many (e.g. Taylor et al., 2009) others have considered the leaves to be lycopsid rather than coniferous (Hübers et al., 2011). This problem was also discussed by Scott and Chaloner (1983). Other early conifers have been discovered in the Middle Pennsylvanian of England subsequently (Galtier et al., 1992). Moscovian charred conifers, especially represented by charred leaves, have been described from Illinois (Scott et al., 2010). However, the horizon from which the *Swillingtonia* charred leaves occurred also contained other material (Scott, 2018) that was indicated in Scott (1978) from Swillington Bed 20f. Although the material was mentioned none was studied or illustrated.

We can consider the diversity of plants preserved as compression fossils in the clastic sediments of Swillington. These include lycophytes, not only stems (such as '*Lepidodendron*' and *Sigillaria*) but also rooting systems such as *Stigmaria*, leaves such as *Cyperites*, shoots such as *Bothrodendron* and a range of cones.; Sphenophytes such as *Calamites* (stems), leaves such as

*Asterophyllites* and *Annularia*, cones and *Sphenophyllum*; pteridosperm foliage including species of *Alethopteris*, *Neuropteris*, *Paripteris, Laveineopteris*, *Mariopteris*, Karinopteris, *Sphenopteris*, *Eusphenopteris*; ferns such as *Renaultia*, *Zeilleria*, *Pecopteris* and *Palmatopteris*; *Cordaites*, mainly leaves and also the coniferous leaves (*Swillingtonia*). The diversity was greatest in the floodplain sediments where it is believed most of the plants lived.

Within Bed 20f (Figure 2) that is approximately 30 cm thick 14 units were originally identified (Scott 1978, Table 1). While charcoalified plants were recorded mainly from Bed 20f9 they also occur in other horizons. Subsequent sampling and maceration of this bed revealed that charcoalified plants were more common that previously realised. What became obvious was that much of the charcoal was of leafy fragments and not woody material that is more often recorded. In some respects this may not be surprising as bulk maceration of a few of the sediments containing charcoal demonstrates, a variety of charred plant organs may be found (see Scott, 2010; Scott et al., 2014) but there have been no systematic studies of charcoalified vegetation dominated by leaves. Charred leaf charcoal was discussed by Remy (1954) but this was prior to the development of the scanning electron microscope that is needed for the study of such material. We should not be surprised as there are few modern studies of charred vegetation (see Scott et al., 2000) or even of Quaternary or Holocene charcoals (see Scott et al., 2017 for discussion).

One of the most significant problems is the identification of charred foliage. Many features used in species identification include pinnule variation, attachment as well as frond organisation. Such features cannot be used to identify fragmentary charcoalified specimens. In addition, comparing Scanning Electron Micrographs of charred specimens with prepared cuticles viewed in transmitted light can be difficult as each preservation state preserves different features. For example, glandular hairs and papillae are well seen in the charcoalified material, as are overarching papillae associated with stomata, while some of these can only be seen in exceptionally preserved cuticular material.

While it is not possible to provide definitive species lists, the illustrations of the charcoalified material presented here allow several conclusions to be drawn.

### *4.2.1 Lycophytes*

Most of the charred lycopsid material represent isolated leaf cushions (Plate I). What was surprising was that there were no charred *Cyperites* leaves identified but it is possible that the arborescent lycopsids were relatively few on the landscape and that the long leaves were flammable and were mostly burned and that any fragments preserved as charcoal would be fragile and difficult to identify. This is the case, for example, today where large areas of grassland are burned but charred grasses are relatively rare (Wooller et al., 2000). In such cases the leaves are almost completely consumed by the fire (Saiz et al., 2018). Another possibility is that when a tree was struck by lightning then the upper portion with dense leaves burns but if there is no canopy interconnection (Figures 4,5) then only the upper part burns, as in the case of some trees in tropical rainforest (Cochrane, 2009).

### *4.2.2. Sphenophytes*

Again charred material appears to be relatively rare. It is possible that many of the plants are found in the riverside ‘reed’ beds (Scott, 1979) that do not catch fire. Only one example of a charred *Calamites* stem was found at Swillington (Plate II, 1) and fragments of charred *Asterophyllites* foliage appears to be relatively rare (Plate II, 2-4). As the plants may have grown in relatively wet environments, even with their roots in waterlogged soil such biomes may have been less susceptible to fire. Although *Sphenophyllum* occurs in the compression assemblage (Scott, 1976, 1984) no definitive charred material has yet been identified. The cuticles of these plants are known (Libertin et al., 2014) and hence identification may be possible.

### *4.2.3. Ferns and pteridosperms*

Ferns and pteridosperms that are widely represented in plant compression assemblages (Bashforth et al., 2016a,b; Šimůnek, 2004) are represented by a large range of charred pinnules. There are numerous genera and species represented but for the most part these can not be securely identified but the number of different types indicate a considerable diversity. The pinnules include the well-known genera of *Neuropteris* (Cleal, 2002, Cleal and Schute, 1991; 1992, 1995, 2012; Cleal and Zodrow, 1989), *Paripteris* (Šimůnek, 2009, 2010), *Laveineopteris* (Cleal and Schute, 2003; Šimůnek and Cleal., 2013, 2020), *Alethopteris* (DiMichele et al., 2006; Šimůnek, 1988, 1989; Šimůnek, and Cleal, 2002), *Mariopteris* (Wang et al., 2019), *Eusphenopteri*s, and a large number of forms that may be included in the broad genus *Sphenopteris* (see Šimůnek 2007a; Šimůnek and Cleal, 2020. The neuropterid forms such as *Neuropteris* (Cleal and Schute, 1992; DiMichele et al., 2006) and forms now attributed to *Laveineopteris* (Cleal and Schute, 1992; Schute and Cleal, 2002; Šimůnek and Cleal, 2013) and *Paripteris* (Šimůnek, 2010) are all known as compression fossils in the compression assemblages at Swillington and may be represented in the charred material (Plates III, IV). While some taxa appear to have a relatively simple stomatal apparatus, different species of the same genus appear to have overarching papillae and other papillate cells on the leaves but these are often indistinct in the cuticle preparations. Likewise *Mariopteris* (Wang et al., 2019) may also be present in the charred pinnule assemblage as is *Sphenopteris* or even *Eusphenopteris* (Chen et al., 2017). The cuticle of *Eremopteris* has also been described (Cleal et al., 2009) and may be present in the material and distinguishing ferns from pteridosperms in the charred material may prove problematic. We know for example ferns such as *Renaultia* but other forms of fern-like foliage such as *Zeilleria* and *Palmatopteris* could be represented in the charred material (Plates III-XI), but few taxa have been described as regards their epidermal structure (but see Krings et al., 2003; Šimůnek and Cleal, 2002; Bek and Pšenička, 2001; Pšenička and Bek, 2003). The spore

*Raistrickia* and other fern spores have been found in palynological preparations from Swillington (Scott, 1976, 1978; Highton et al., 1991) and indeed many of the palynodebris samples from the sediments throughout the Swillington succession contain charcoal (fusain) fragments (Highton et al., 1991). What is clearly evident is not only the range of pinnule morphology but also stomatal types from simple stomata to those with overarching papillae. These papillae have been thought to indicate a xeromorphic adapation of the plants that may suggest a susceptibility to wildfire events but recent studies have also suggested that they had a function of helping plants to live in very wet humid conditions or in some cases were a physiological relic (Stull et al., 2012; Cleal and Schute, 2012).

What we also see in the assemblages are a large number of spiny stems, both wide and thin (Plate VII) as well as isolated hooks (Plate III) suggesting that some of these plants may be scrambling, possibly even lianas (Krings et al., 2003; Šimůnek and Cleal, 2002). This has implications as to the nature of the fires, as climbing plants may act as ladder fuels (Figures 4,6). While charred medullosan stems have been studied (Zodrow et al., 2010), their anatomy has been largely neglected (see Plate VIII).

What is surprising is the lack of charred fertile organs. Such charred fertile organs have been found in Mississippian charred plant assemblages (Scott et al., 1986, 2019; Scott, 2010) but their absence may reflect the timing of the fire event(s).

### *4.2.4. Cordaites and conifers.*

The final group of plants are represented by other gymnosperms, *Cordaites* and conifers. Charred leaf fragments of *Cordaites* are frequent and may show distinctive glandular hairs (Plate X) (see Šimůnek, 2007b, 2018, 2019; Šimůnek and Florjan, 2013). As indicated earlier rare leafy shoots and leaves of the putative earliest conifer *Swillingtonia* also occur (Plate XI). Charred wood material is also found (Plate IX) but the material may also include other tissues from a range of taxa including pteridosperms (Plate VIII). The wood has many different types of pitting indicating an origin not only from *Cordaites* but also possibly from pteridosperms. In these cases identification of fragmentary material can be difficult. The problems of identifying such material has been discussed by Clack et al. (2020).

### *4.3. The interpretation of charred assemblages.*

It is clear that most of the plants preserved were of generally low stature, most commonly shrub-like, rather than being from a forested-dominated biome. It is likely, therefore, that this represents a surface fire regime and the larger plants could be burned via the abundance of ladder fuels as indicated by vine-like or liana-like plants and suggests that the living vegetation may burn relatively easily (Figure 6). The fire type may be similar to a modern heathland fire (Scott et al., 2000) where fires may be relatively slow burning and living leaf material may be easily preserved as charcoal. Any small movement of the charcoal by wind or water may create leaf versus wood-rich horizons (Scott et al., 2000; Scott, 2000, 2010). What is evident is the general lack of fungal infestation of the material (but see Plate VI, 5) that may suggest most of the specimens represent charred foliage from living plants rather than that of charred litter. However, charred leaves from modern wildfire assemblages appear to have been derived from the litter so that it is possible that the litter represented a single year of accumulation rather than have been part of a decaying litter layer that had accumulated over many years.

## **5. Implications concerning Carboniferous wildfires**

What lessons can be learned from this material concerning Carboniferous (Pennsylvanian) wildfires? Perhaps the most obvious lesson is that not all charcoal is derived from wood. This may seem obvious however, this is often the most recognizable material and the most regularly described (Uhl et al., 2004, Uhl, and Jasper, 2021; Jasper et al., 2011, 2013; Benicio et al., 2019; Falcon-Lang, 2000, 2003; Falcon-Lang and Scott, 2000). What is also evident is that charred foliage may be more common than generally appreciated and may not be identified from bedding surface inspection and it requires bulk maceration of the material (Pearson and Scott, 1999) for it to be identified (Scott, 2010; Glasspool and Scott, 2013). Only when systematic bulk maceration for charcoalified leaves in silts and muds are undertaken may a true understanding of their occurrence be achieved. Transport of charred material, mainly by water transport, is likely to separate charred wood from other charred plant organs, just as has been noted in several Cretaceous assemblages (see Brown et al., 2012) for a discussion.

The second lesson from this study is that fires occur in different sedimentological contexts and that different vegetation types are involved (Figure 7) (DiMichele et al., 2006; DiMichele and Falcon-Lang, 2011; DiMichele and Phillips, 1985, 1996, 2002). We also need to consider the dynamics of the fire and to consider the spread of surface and crown fires (Scott et al., 2014).

The third aspect depends on how the relationship between the coal and the clastic environments is interpreted. In my original interpretation of the Swillington sedimentary log, I considered that the peat and clastics were coeval and that fires could spread between these different ecosystems – fire frequency may, therefore, be related (Figure 7).

If, however, the peat-forming system and the clastic sedimentary system are sequential and represent slightly different climate states then we need to consider the fire regimes separately. While there is a realization of significant fluctuation of $CO_2$ through the different intervals the $O_2$ levels appear to have been consistently above the modern level of 21% (Glasspool et al., 2015, Lenton et al., 2018).

In recent fire systems there has been increasing interest in the relationship between $CO_2$, climate and vegetational change through the emissions of fire or in the burial of charcoal formed as a result of fires (Page and Hooijer, 2006; Jones et al., 2019). This interest has also led to further consideration of the use of biochar to reduce atmospheric $CO_2$ (Lehmann et al., 2006; Masek, 2013). The role of fire both in affecting and be affected by climate change is of increasing concern (Moritz, 2012; Moritz et al., 2012; Krawchuk et al., 2014) and also the role of fire in affecting ecological systems (Odion et al., 2010; Whitlock et al., 2010 see also Bond et al., 2005).

How fire may impact on the $CO_2$ story is as yet uncertain but may be significant both on the long and short timescales in providing rapid release of $CO_2$ by frequent fires but then locking up carbon by producing large amounts of charcoal (see also Finkelstein et al., 2006 for a discussion).

The impact of atmospheric change on both the climate and plant physiology and ecology is an area of increasing interest for the Carboniferous (see DiMichele et al., 1996, 2009, 2010; Falcon-Lang and DiMichele, 2010; Montanez et al., 2007; Richey et al., 2020, 2021; Wilson et al., 2015, 2017, 2020; Tabor and Poulsen, 2008; Opluštil and Sýkorová, 2018; Poulsen et al., 2015) but none of this studies have fully integrated our understanding of wildfire nor their potential impact upon not only the vegetation (Bond et al., 2005) but also on a glacial-interglacial system (see Keegan et al., 2014)

## 6. Conclusions

There has been an increasing appreciation of the importance of wildfire in the Carboniferous Earth System over the past 30 years (compare Scott and Jones, 1994; Falcon-Lang, 2000; Scott 2000, 2010, 2018) and especially the role of high atmospheric oxygen contents that allows more fire in the landscape (Beerling et al., 1998; Scott and Glasspool, 2006; Glasspool et al., 2015; Belcher et al., 2013, Kump, 2010; Lenton et al., 2018). Despite this, our understanding of fire in a range of Carboniferous biomes and during a range of different climate states is still at a very primitive level. The results from this study provide some useful additional data but also highlights some significant deficiencies and problems, some of which may be difficult to resolve.

Fire was an important element in the Earth System during the Carboniferous. Yet still while there is an appreciation of the relationship between changing $CO_2$ levels and climate change during this Period and that there is also raised atmospheric oxygen, there is no corresponding appreciation of the potential role both in wildfire moderating climate change. Nor is there an appreciation of the potential role of fire in driving some aspects of plant evolution. This is particularly surprising as the late Paleozoic represents one of the two highest atmospheric oxygen intervals through the Phanerozoic (Lenton et al. 2018). The other period of high atmospheric oxygen level in the Cretaceous (Lenton et al., 2018; Scott, 2018) was not only a period of major wildfires (Brown et al., 2012) but these wildfires are thought to have played a significant role in the evolution of several plant groups (Bond, 2015; Bond and Keeley, 2005; Crisp et al., 2011; Keeley et al., 2011; Lamont et al., 2018; Pausas, 2019; Pausas and Keeley, 2009) and indeed was responsible for selecting a range of fire-adapted traits in a range of plants (Bond and Scott, 2010; He et al., 2012, 2016; Pausas and Keeley, 2019).

In this study it has been shown that fire was an important element in the peat-forming mire system with a high background level of inertinite (charcoal). Peaks of over 20% inertinite representing major fires were shown to occur both in the wetter and drier phases of peat development but more often in the drier phases with a fire return interval of less than 500 years. If the clastic and peat-forming systems were co-eval then fires may spread across a much larger range of ecosystems. However, if the peat-forming and clastic systems were sequential as a result of change in climate, especially rainfall, then the fire systems may not be connected. More data is needed to develop the link between fire, vegetation, atmospheric and climate change in the Pennsylvanian.

Within the peat (coal)-forming mire settings the type of fire (ground, surface, crown) will depend on the wetness of the substrate. It should be noted, however, that wetter plants may burn with high atmospheric oxygen concentrations (Watson and Lovelock, 2013). The spread of surface fire may be difficult in many mire types such as in rheotrophic swamp systems where the surface conditions are persistently wet. In these circumstances, fires may be confined to the crowns of the trees and fire spread will be directly controlled by canopy interconnectedness. Fire frequency may potentially only be calculated from such coal sequences but there are a large number of issues that would need to do this to provide realistic data. Particular attention would need to be made of sample collection and preparation. Lateral variation on vegetation may also have an impact on fire spread and hence size.

The results of the current study indicate that there is abundant evidence of surface fires in vegetation dominated by pteridosperms. Such material has rarely been reported or described possibly from the methods used to study fossil plant assemblages from clastic sediments where the plants are predominantly preserved as compression fossils and bulk maceration of sediments is not routinely employed. We note, for example, that in other geological periods a range of charcoalified organs have been recovered using bulk maceration techniques (Friis et al, 2006; Collinson et al., 2000). Isolated records of charcoal mean that fire size may be rarely estimated. There have been few attempts thus far to link fire in these lowland clastic settings to aspects of sedimentological change. The results of the current study also indicate that a diversity of different pteridosperms were subjected to wildfire. I should also note here the linkage to fire and phosphorous that may have an impact both upon terrestrial systems and upon ocean productivity (Kump, 1988).

There is evidence of fire in cordaite/conifer vegetation with both leaves and woody material preserved as charcoal. This material may derive from lowland vegetation associated with the predominantly shrubby pteridosperm dominated biomes.  Some may also be derived from extra-basinal areas transported by water as a result of run-off from post-fire erosion (see for example Falcon-Lang, 1999; Falcon-Lang and Scott, 2000). This has been reported in other geological intervals (e.g. Brown et al., 2013; Muir et al., 2015). In addition such material may be transported by lofting and widespread wind distribution, especially if fires are common in such extra-basinal settings (see Scott et al., 2000; Scott, 2020 for a discussion).

In view of the widespread occurrence and significance of fire in the late Paleozoic Earth System more attention needs to be paid to its role not only in atmospheric composition control, climate implications but also in the potential role of driving the evolution of plants and a consideration of fire traits in plants (as has recently be considered in Permian conifers (Looy, 2013)).

## Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Explanation to Figures

Figure 1. Location of Swillington Brickpit and the St. Aidans Extension core.

Figure 2.The Swillington Brickpit, Yorkshire, England.

a. Photo taken in the early 1990s showing the exposed sequences and the position of bed 20.
b. Lithological log of section with detail of Bed 20f (after Scott, 1978).

Figure 3. Section through the Low Barnsley Coal showing megaspore phases and their interpretation (after Bartram, 1987b) with inertinite distribution (from Scott, 2000) with interpreted fire events using peaks above 20% inertinite background.

Figure 4. A typical tropical Carboniferous ecosystem (based upon Gastaldo et al., 2004) with position of fuel and fire types.

Figure 5. Ledidodendrid trees with a range of architecture and fire types. Generalised examples from left to right: juvenile arborescent lycopsid, *Paralycopodites*, *Sigillaria, Lepododendron* SL/*Lepidophlois*.

Figure 6. Typical Medullosan shrub with climbing liana-like plant (after Taylor et al., 2009) acting as a ladder fuel to join a surface to a crown fire.

Figure 7. Interpreted palaeoenvironments of the Swillington Brickpit, Yorkshire (based upon Scott, 1978 and Highton et al., 1991).

Explanation to Plates

I. Scanning Electron Micrographs of charcoalified lycopsids from the Middle Pennsylvanian of Swillington, Yorkshire, England. Bed SW20f9

1. Type 1 Lepidendroid leaf cushion.
2. Type 2 Lepidodendroid leaf cushion. Specimen SW20f3b
3. Detail of cushion surface in Figure. 1.
4. Detail of 3 showing sunken stoma on leaf cushion suface.
5. Surface of type 2 (see Figure 2).
6. Lycospora on surface of Leaf cushion in Figure 2.

II. Light and Scanning Electron Micrographs of charcoalified Sphenopsids from the Middle Pennsylvanian of Swillington, Yorkshire, England.

1. Piece of Charcoalified Calamite stem. SW Bed 13.
2. Charcoalified *Asterophyllites* foliage. Bed SW20f9
3. SEM of charcoalified *Asterophyllites* foliage. Bed SW20f9
4. Detail of Figure 3 showing stoma.

III. Scanning Electron Micrographs of charcoalified Pteridosperms from the Middle Pennsylvanian of Swillington, Yorkshire, England.Bed SW 20f.

1. Alethopterid leaf. SW20f9. Specimen SW20f19d
2. Alethopterid leaf. Specimen SW20f20e
3. Alethopterid leaf. Specimen SW20f18b
4. Alethopterid leaf. SW20f9; Specimen SW20f19a
5. Stoma on Alethopterid leaf see in 4. .

6. Isolated pteridosperm hook (Type 2). Specimen SW20f28j

7. Spiny pteridosperm axis (Type 1). Specimen SW20f32d.

8. Terminal fragment of type 1 Neuropterid-like foliage. Specimen SW20f24f

9. Detail of 8 showing papillae and hairs surrounding stoma.

10. Pteridosperm foliage fragment. Specimen 20f2-1

11.Detail of 10 showing several simple stomata.

IV. Scanning Electron Micrographs of charcoalified fern-like foiliage from the Middle Pennsylvanian of Swillington, Yorkshire, England. Bed SW20f

1. Pinnule Type 1. Specimen SW20f4a

2. Detail of 1 showing stomataliferous surface.

3. Pinnule fragment of Type 2 pinnule showing vein hairs and papillate epidermal cells with stomata with overarching papillae. Specimen SW20f19acx

4. Detail of 3,showing papillate epidermal cells with stomata with overarching papillae.

5. Pinnue fragment of Type 2 fragment showing papillate subsidiary cells but simple stomata. Specimen SW20f6a

6. Detail of 5 showing papillate subsidiary cells but simple stomata.

V. Scanning Electron Micrographs of charcoalified fern-like foiliage from the Middle Pennsylvanian of Swillington, Yorkshire, England.

1. Sphenopterid pinnule of Type 3.Specimen SW20f23g.

2. Detail of 1 showing stomata with overarching papillae.

3.Sphenopterid/ Mariopterid-like pinnule. Bed SW20f9

4. Sphenopterid (Eusphenopterid – like) pinnule. Bed SW20f9

5.Detail of 4 showing simple stomata

6. Pteridosperm pinnule Type 5. Showing hairy surface. Specimen SW20f24a

7.Detail of 6 showing papillate stomataliferous surface.

8. Detail of 7 showing papillate subsidiary and epidermal cells.

VI. Scanning Electron Micrographs of charcoalified fern-like foliage from the Middle Pennsylvanian of Swillington, Yorkshire, England.

1. Possible pinnule Type 5 showing papillate surface. Specimen SW20f24c

2.Detail of 1 showing hairs on veins and papillae on epidermal and subsidiary cells.

3. Detail of 2 showing papillate epidermal and subsidiary cells.

4. Pinnule Type 6. Specimen SW20f4D

5. Pinnule Type 7 showing rare fungal hyphae. Specimen SW20f17e

6. Detail of 5 showing simple randomly orientated stomata.

VII. Light and Scanning Electron Micrographs of charcoalified fern-like foiliage from the Middle Pennsylvanian of Swillington, Yorkshire, England.

1. Light photograph of large spiny pteridosperm axis, Type 5, SW20f9

2. SEM of Type 3 spiny axis. Specimen SW20f27c

3.SEM of Type 3spiny axis. Specimen SW20f6b.

4. Detail of 3 showing position of hairs and spines on surface of axis.

5. SEM of Type 3 spiny axis with spines concentrated on one side. Specimen SW20f27a

6. Fragment of Type 3 spiny axis. Specimen SW20f27b

7. Detail of 6 showing epidermal cells.

VIII. Scanning Electron Micrographs of charcoalified woody tissues from the Middle Pennsylvanian of Swillington, Yorkshire, England.

1.Fragile charcoalified axis of possible pteridospem affinity. Specimen SW20f14b

2. Detail of 1 showing tracheids showing multi-seriate pits.

3.Detail of 2 showing detail of pitting.

IX. Scanning Electron Micrographs of charcoalified gymnosperm wood from the Middle Pennsylvanian of Swillington, Yorkshire, England. Bed SW20f9

1. Uncrushed woody fragment of *Dadoxylon* type. Specimen SWf1

2. Detail of 1 showing rays and ray pits.

3.Wood fragment showing rows of bordered pits.

4. Detail of 3 showing pits.

5.Wood fragment.

6.Detail of 5 showing pitting in tracheids and rays.

X. Scanning Electron Micrographs of charcoalified ?*Cordaites* from the Middle Pennsylvanian of Swillington, Yorkshire, England. Bed SW20F9.

1. Type 1 Cordaite leaf showing stomataliferous surface with distinctive papillae. Specimen SW20f25f

2.Detail of 1 showing papillate cells.

3. Detail of 1 showing stoma with papillate epidermal cells.

4. Detail of 1 showing distinctive papilla with lobate top.

5.Cordaite leaf fragment of Type 2. Specimen SW20f25c

6. Detail of 5 showing stomatal rows.

7. Type 1 Cordaite leaf fragment showing range of papillate cells on non-stomataliferous surface. Specimen SW20f13a

8. Detail of stomataliferous area with stomata and papillate epidermal cells.

9. Gymnospermous (? Cordaite/Dadoxylon-type) wood with 3 rows of bordered pits. Specimen SW20f21c.

10. Detail of 9 showing bordered pits in tracheids.

XI. Light and Scanning Electron Micrographs of charcoalified *Swillingtonia* from the Middle Pennsylvanian of Swillington, Yorkshire, England. Bed SW20f9

1. Light photograph of *Swillingtonia* leafy shoot. Bed  SW20f9
2. SEM of *Swillingtonia* leaf showing stomatal rows. Bed SW20f9 NHM V61025
3. Leaf of *Swillingtonia.* Specimen SW20f5a
4. Detail of 3 showing papillate non-stomataliferous epidermal cells.

Figure 1

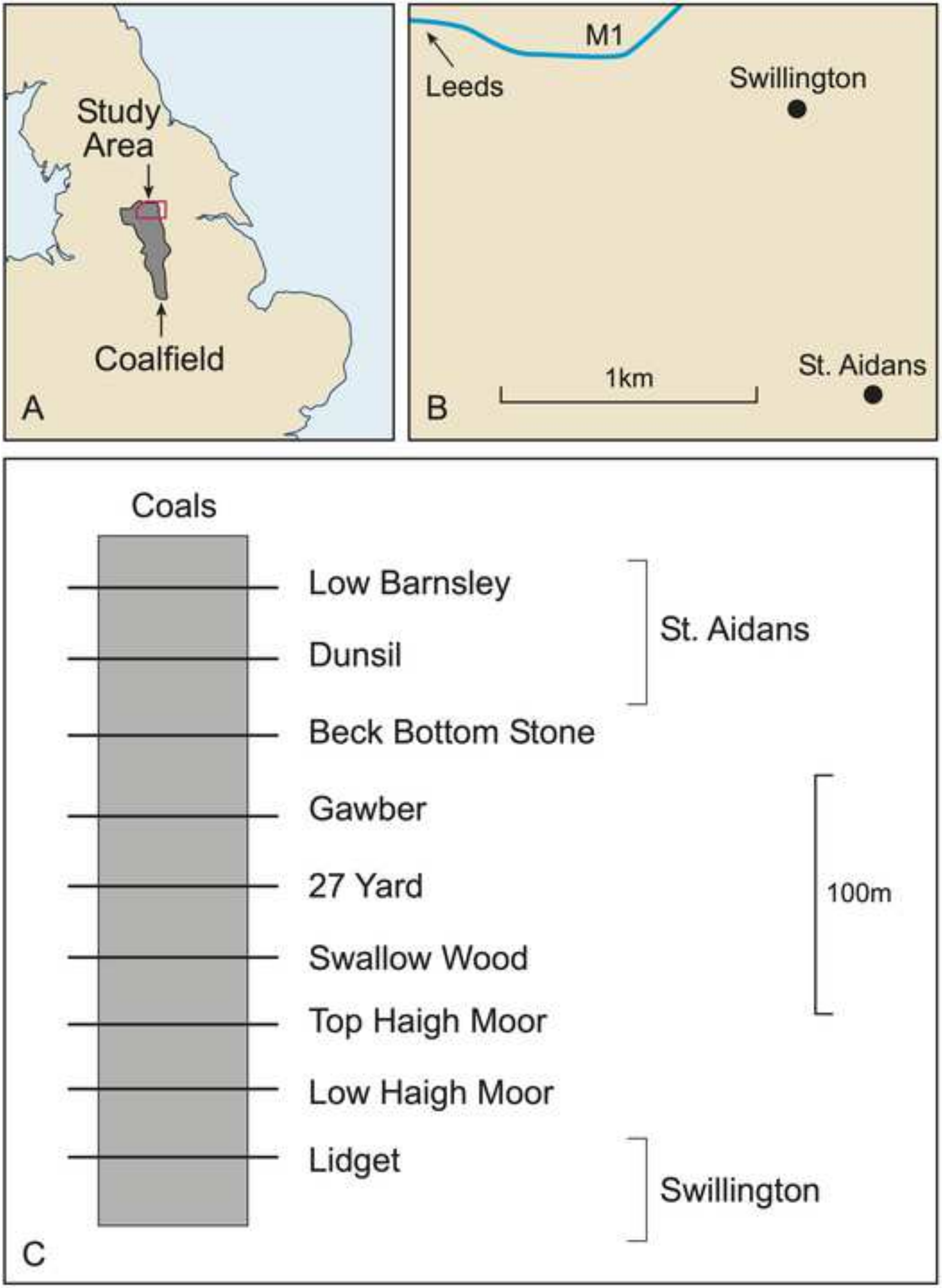

Study Area
Coalfield
A
M1
Leeds
Swillington
St. Aidans
1km
B
Coals
Low Barnsley
Dunsil
St. Aidans
Beck Bottom Stone
Gawber
27 Yard
100m
Swallow Wood
Top Haigh Moor
Low Haigh Moor
Lidget
Swillington
C

Figure 2

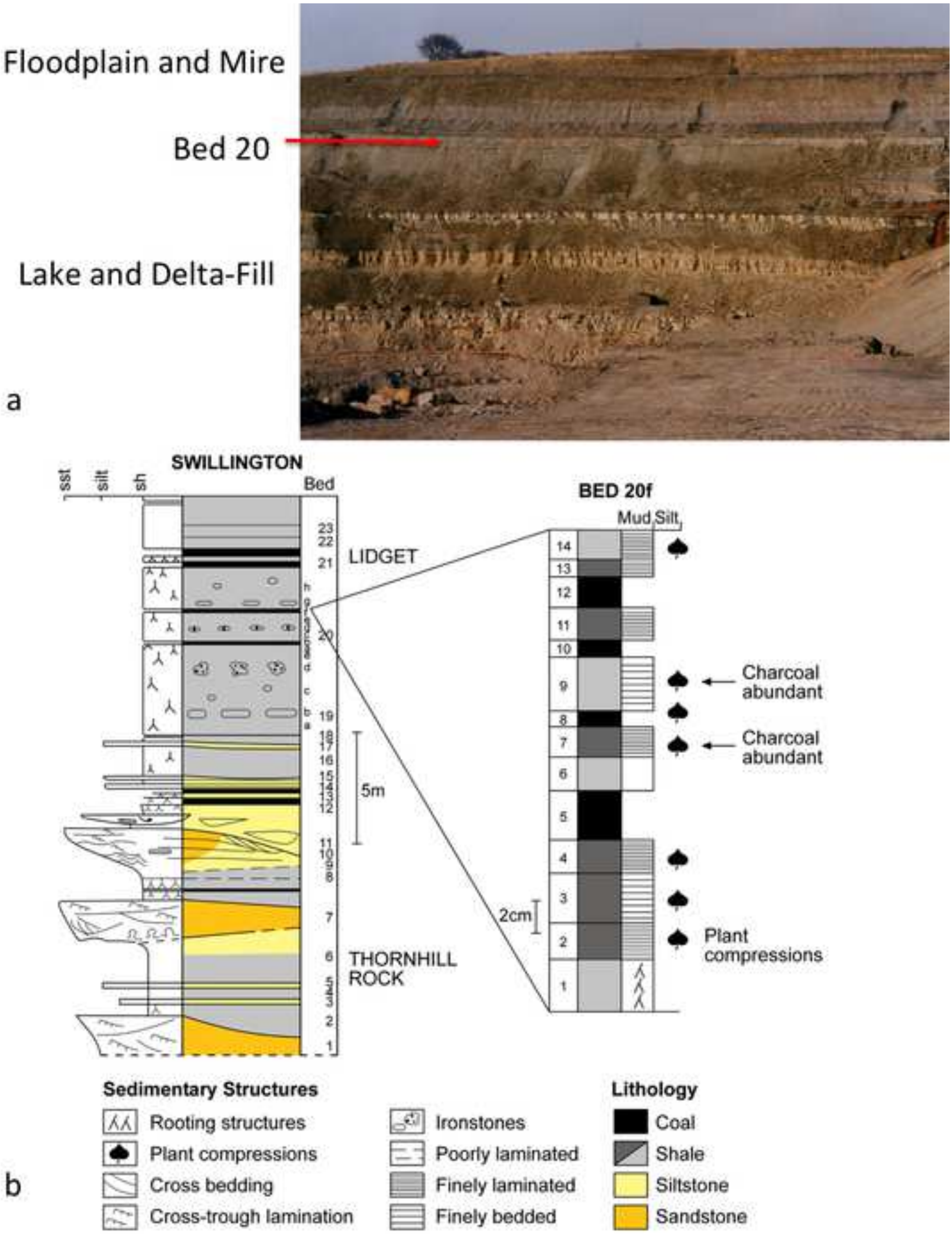

Floodplain and Mire
Bed 20
Lake and Delta-Fill
a
SWILLINGTON
sst
silt
sh
Bed
23
22
21
LIDGET
h
g
20
d
c
b
a
19
18
17
16
15
14
13
12
5m
11
10
9
8
7
6
THORNHILL ROCK
5
4
3
2
1
BED 20f
Mud
Silt
14
13
12
11
10
9
8
7
6
5
4
3
2
1
2cm
Charcoal abundant
Charcoal abundant
Plant compressions
b
Sedimentary Structures
Rooting structures
Plant compressions
Cross bedding
Cross-trough lamination
Ironstones
Poorly laminated
Finely laminated
Finely bedded
Lithology
Coal
Shale
Siltstone
Sandstone

Figure 3

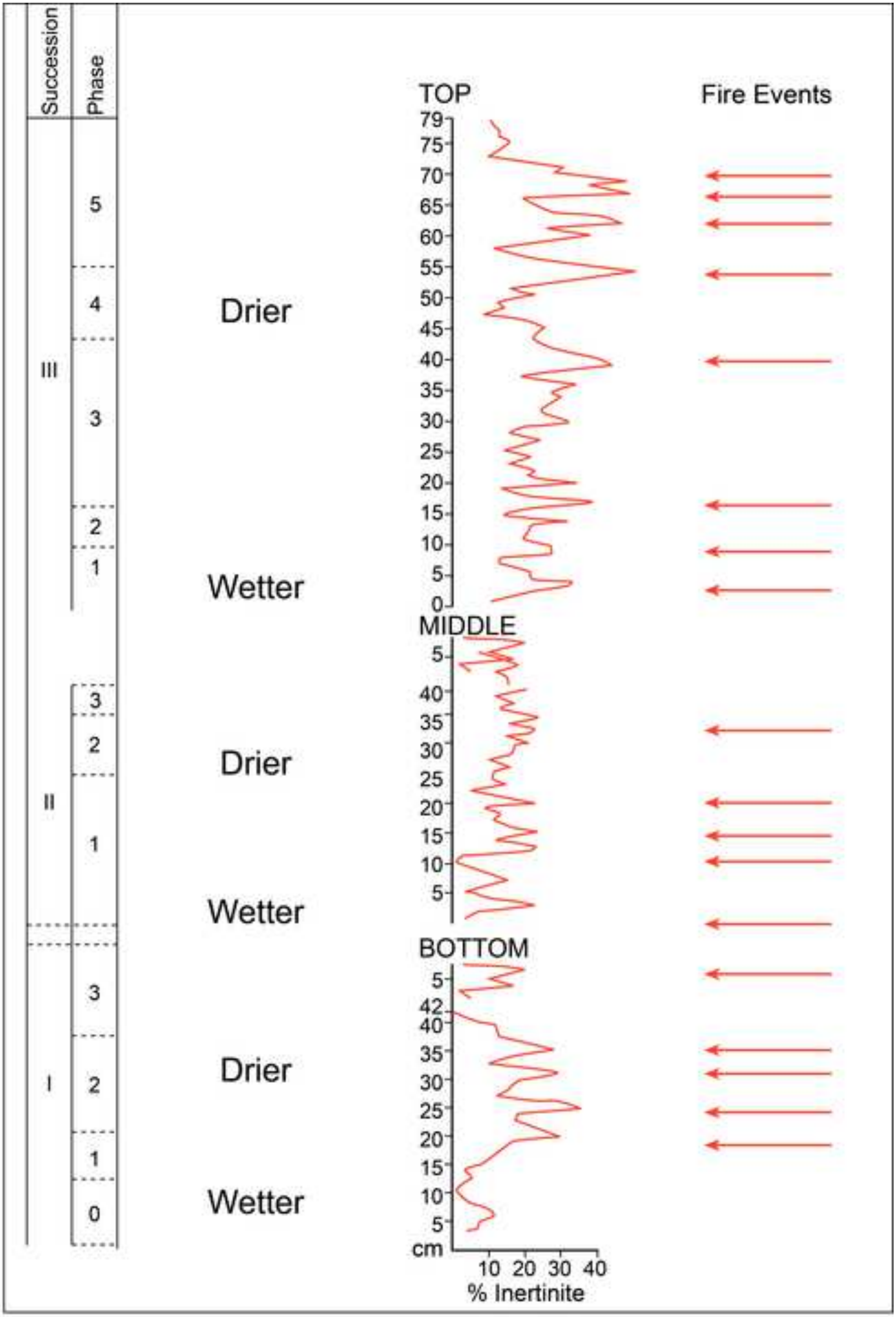
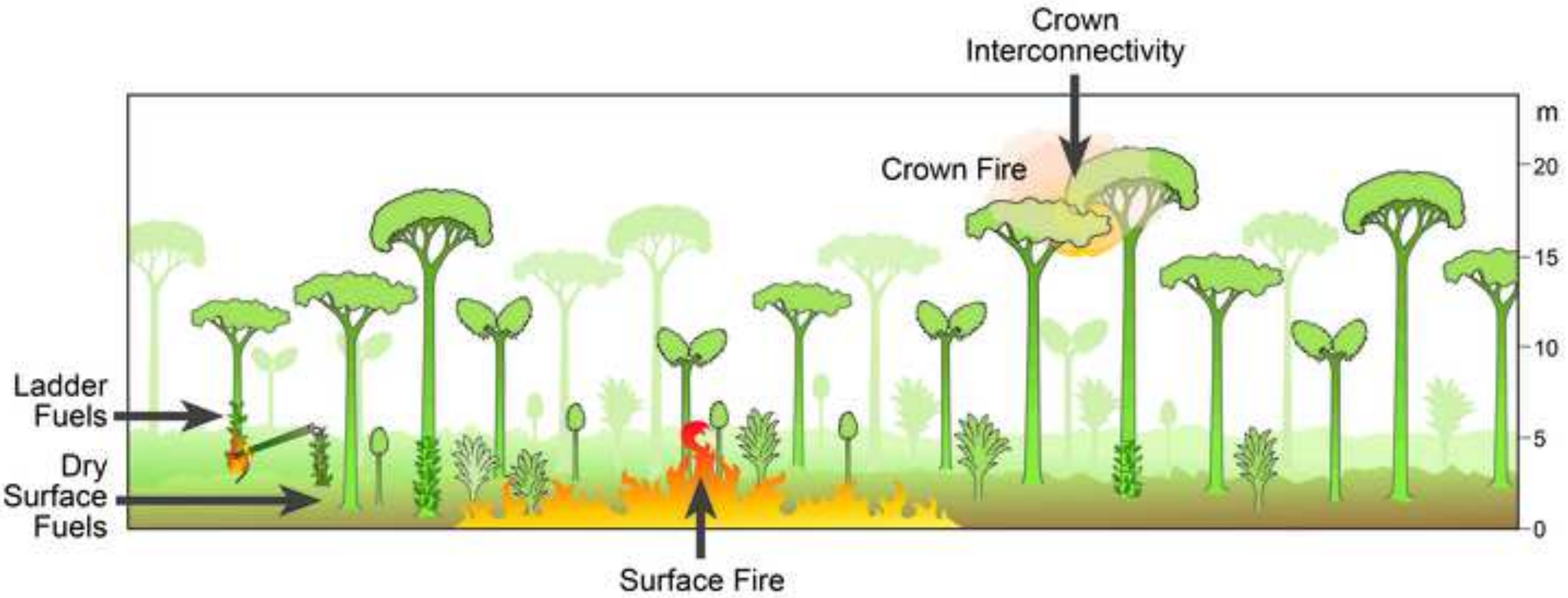
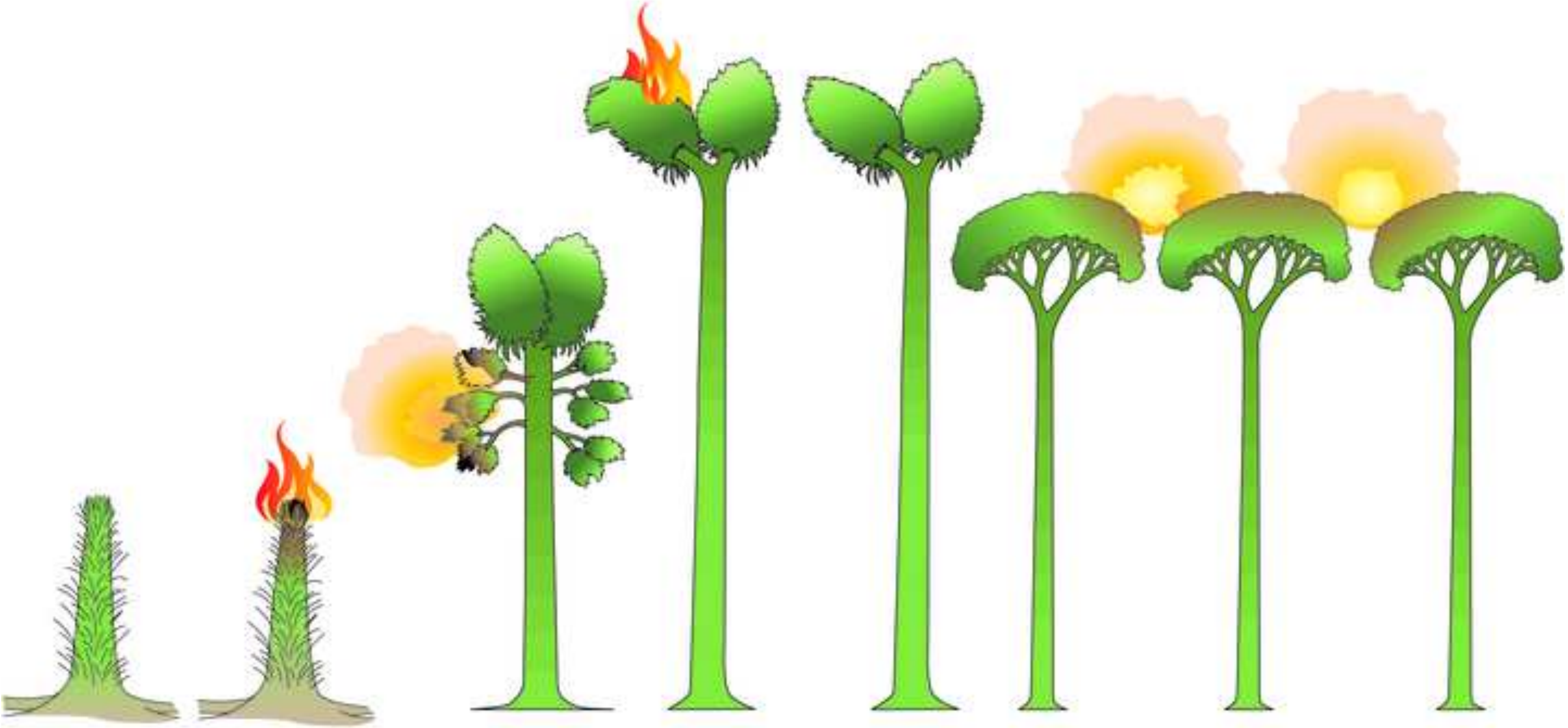

Succession
Phase
III
5
4
3
2
1
II
3
2
1
I
3
2
1
0
Drier
Wetter
Drier
Wetter
Drier
Wetter
TOP
79
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
MIDDLE
5
40
35
30
25
20
15
10
5
BOTTOM
5
42
40
35
30
25
20
15
10
5
cm
10
20
30
40
% Inertinite
Fire Events

Figure 4


Crown
Interconnectivity
Crown Fire
m
20
15
10
5
0
Ladder
Fuels
Dry
Surface
Fuels
Surface Fire



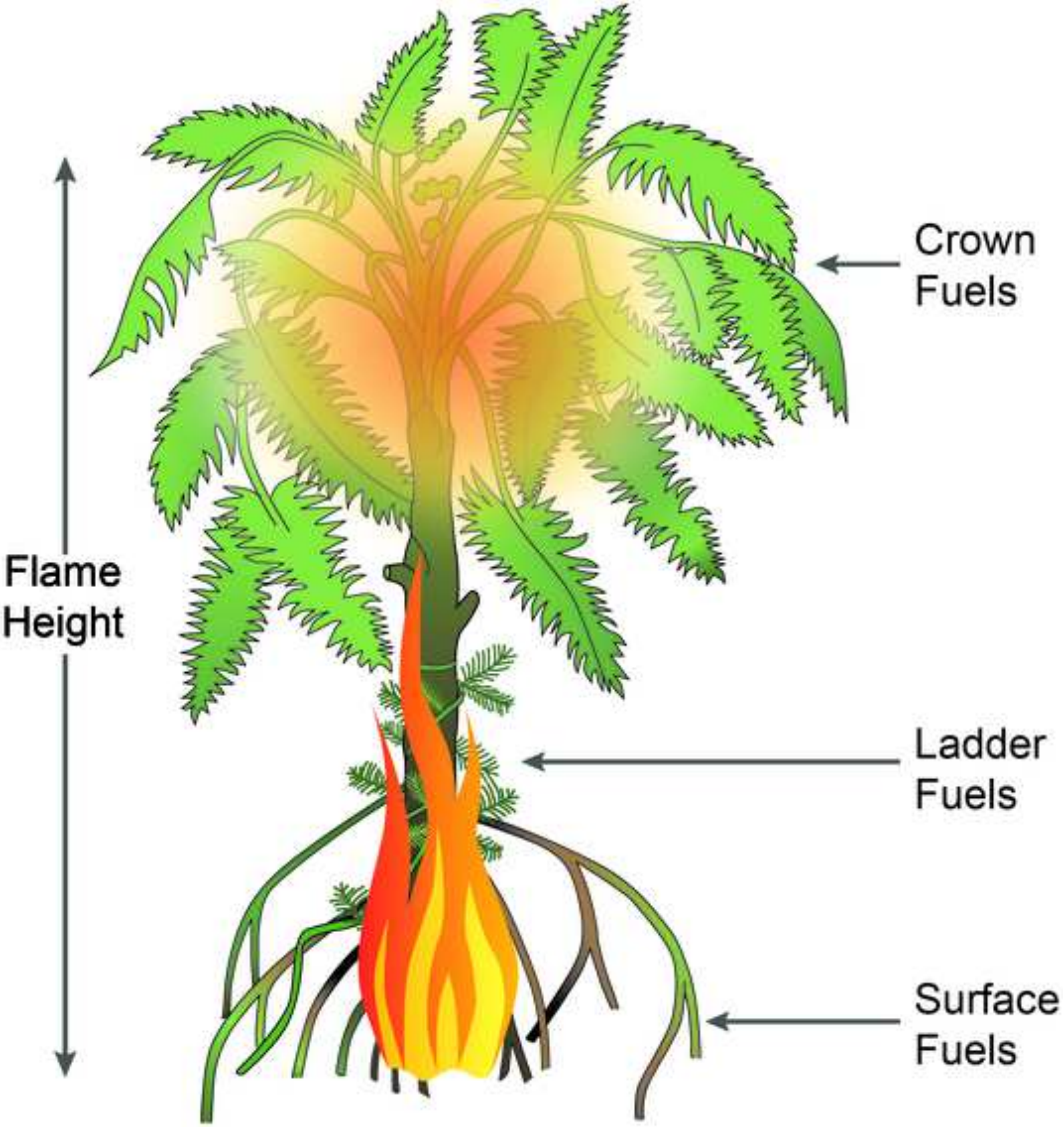

Flame
Height
Crown
Fuels
Ladder
Fuels
Surface
Fuels

Figure 7

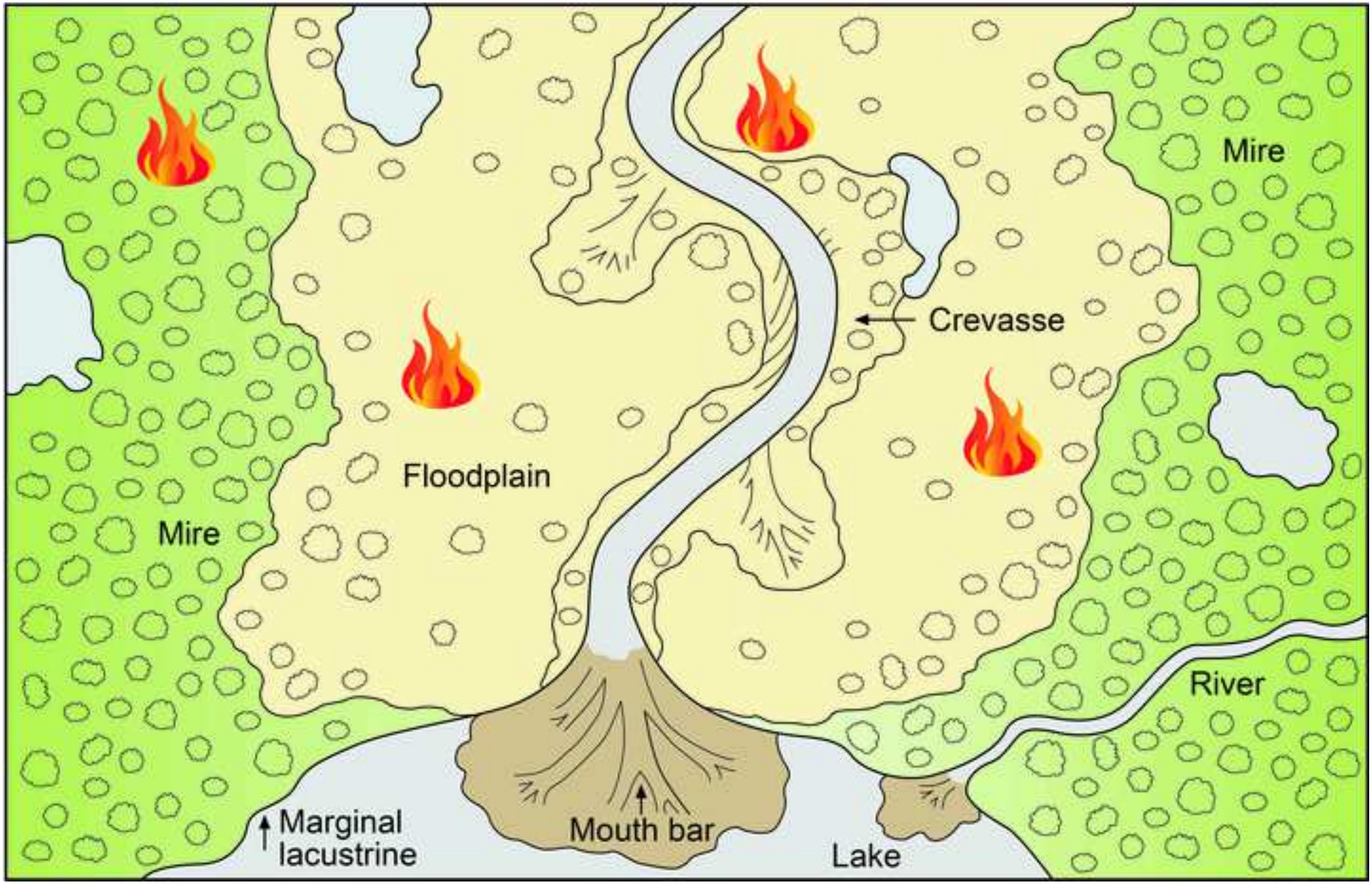

Mire
Floodplain
Crevasse
Mire
River
Marginal lacustrine
Mouth bar
Lake

Plate I

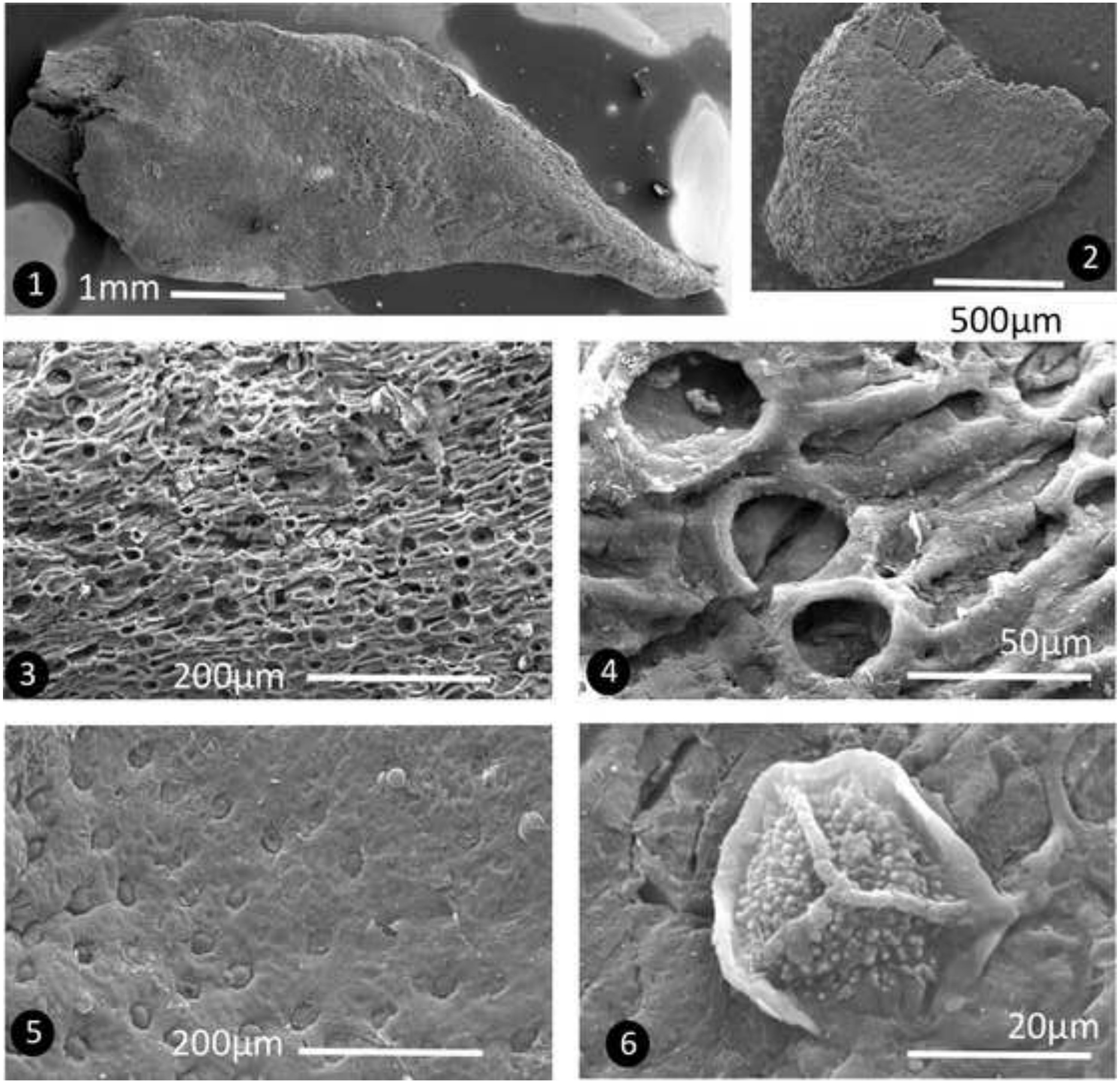


Plate II

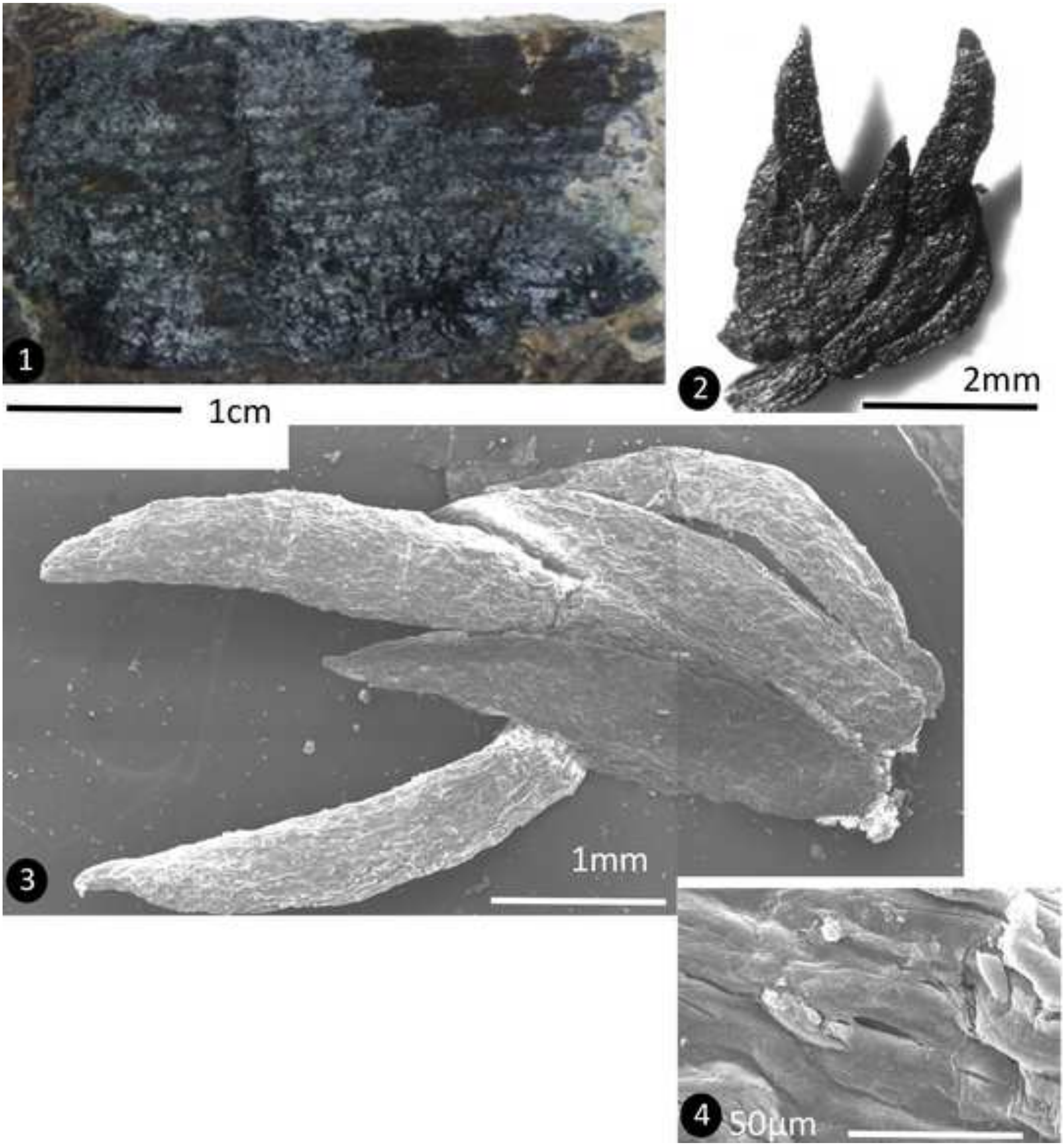


Plate III

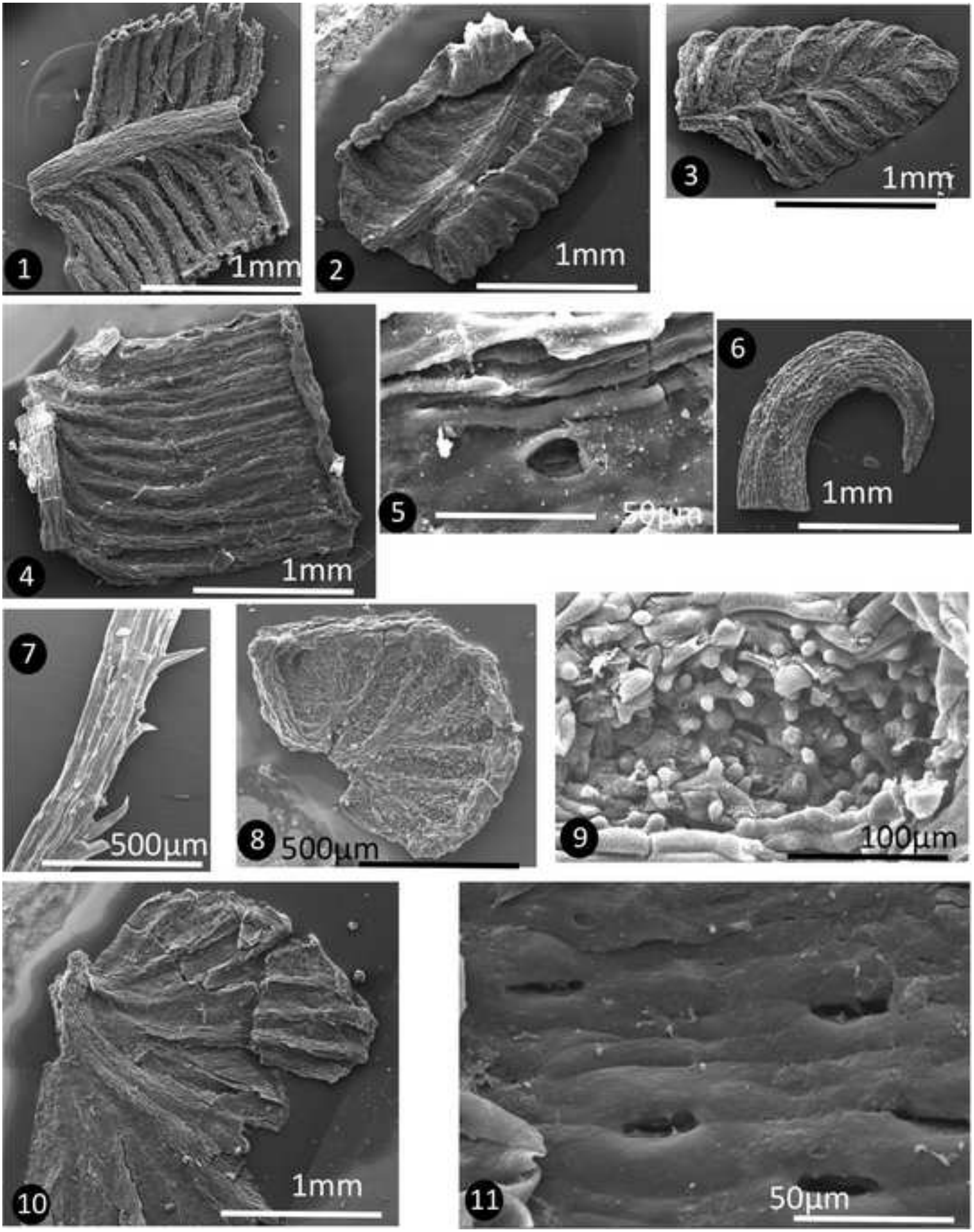

1
1mm
2
1mm
3
1mm
4
1mm
5
50µm
6
1mm
7
500µm
8
500µm
9
100µm
10
1mm
11
50µm

Plate IV

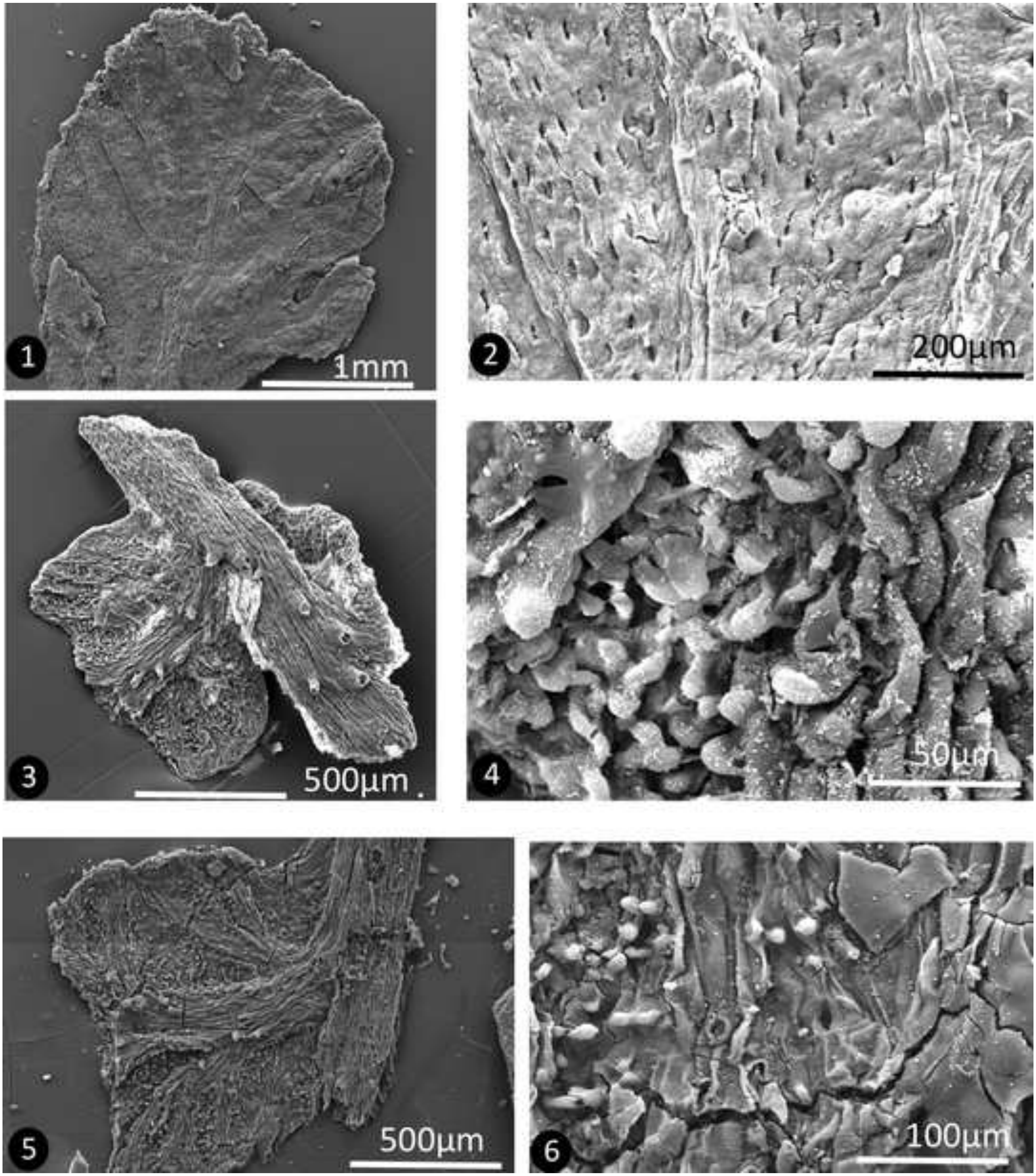
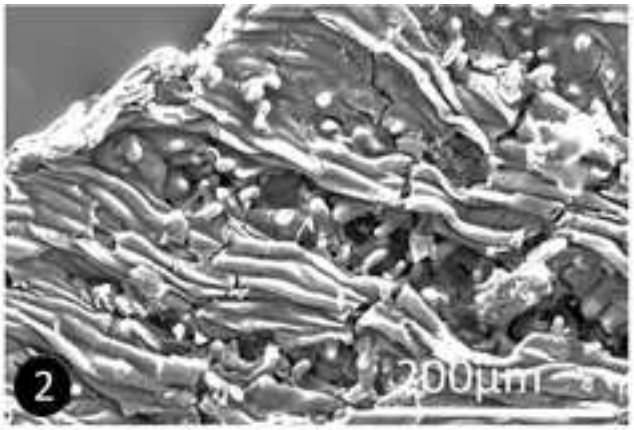


Plate V


1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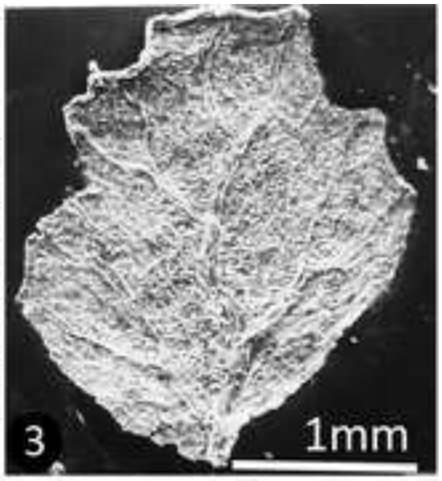
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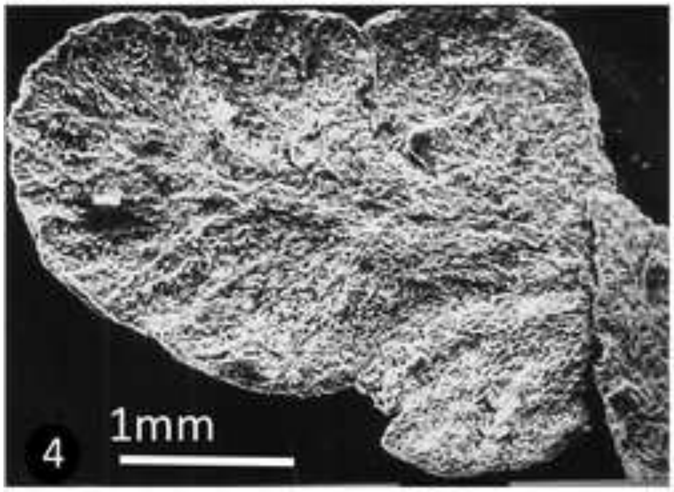
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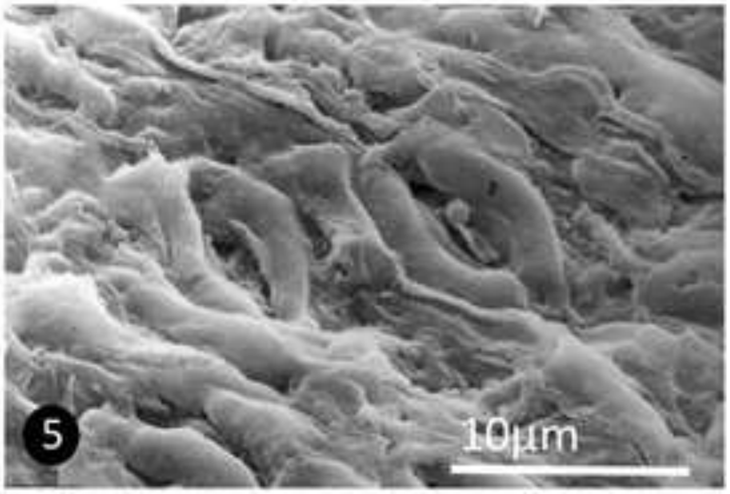
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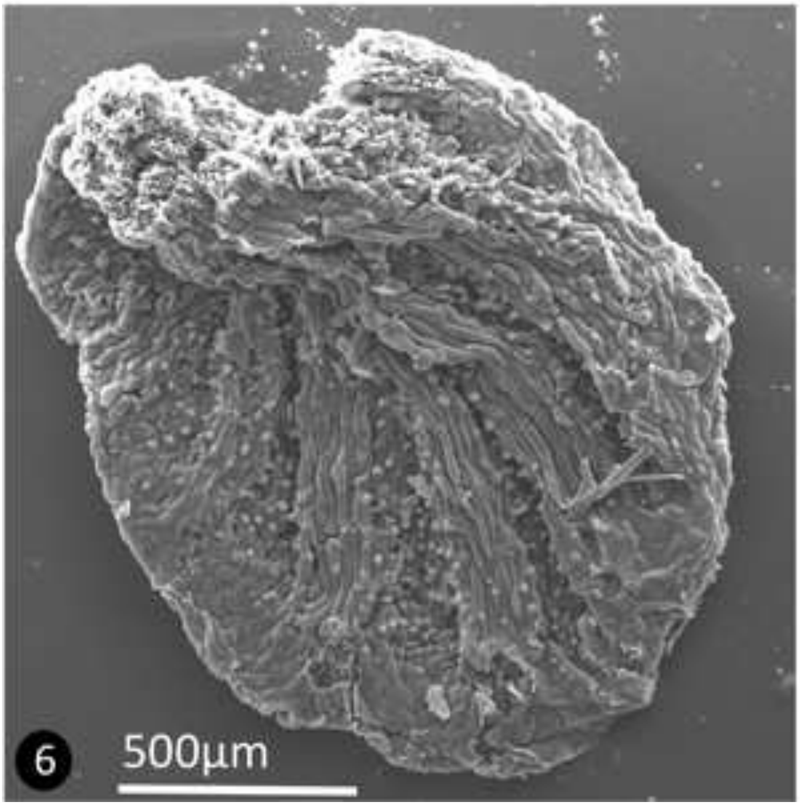
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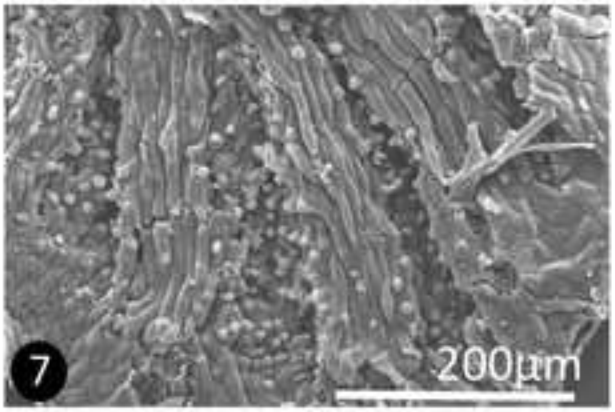
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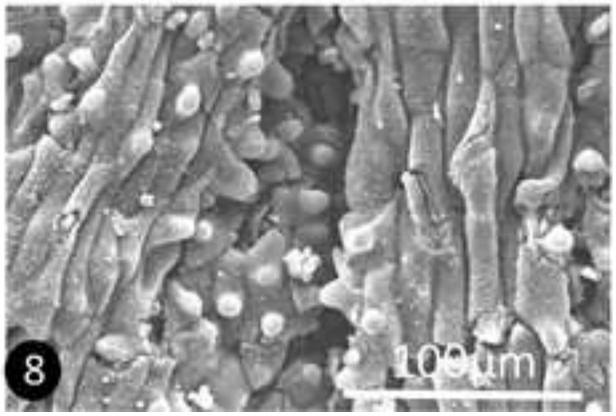
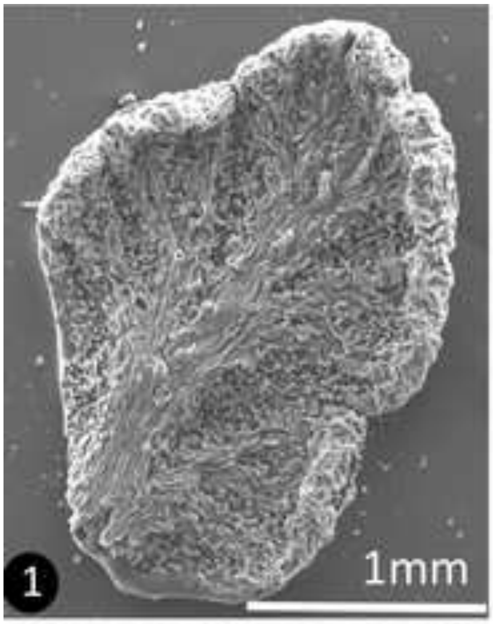
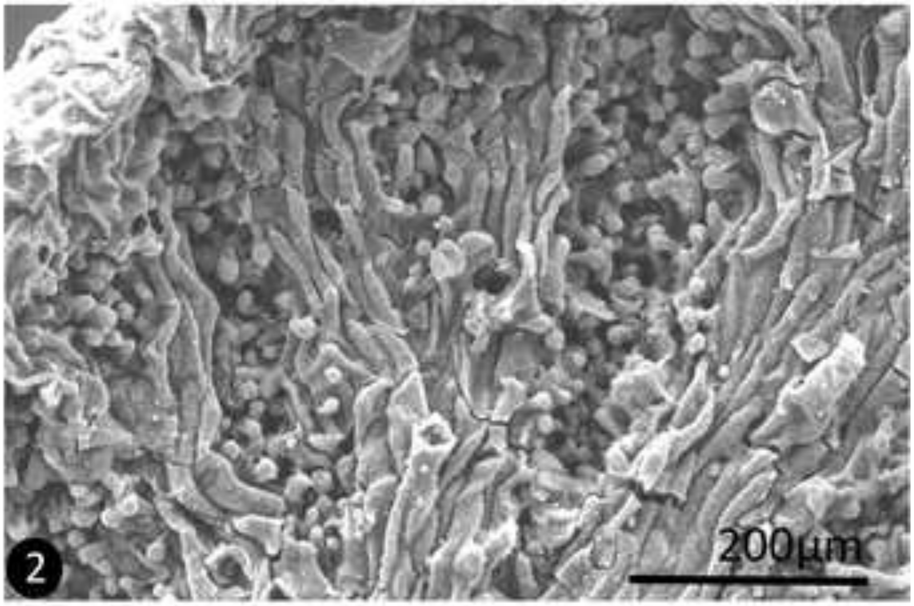
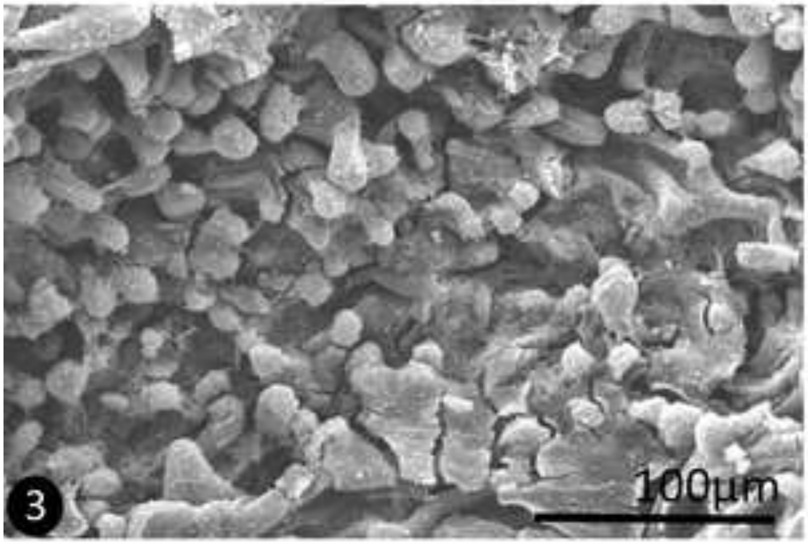
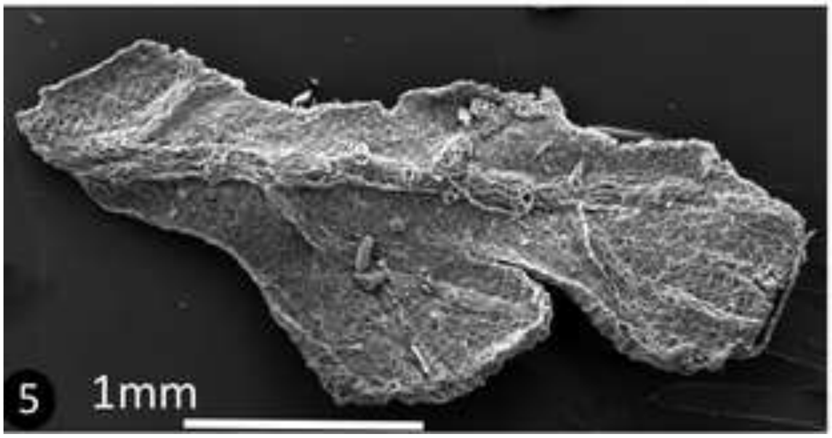

8

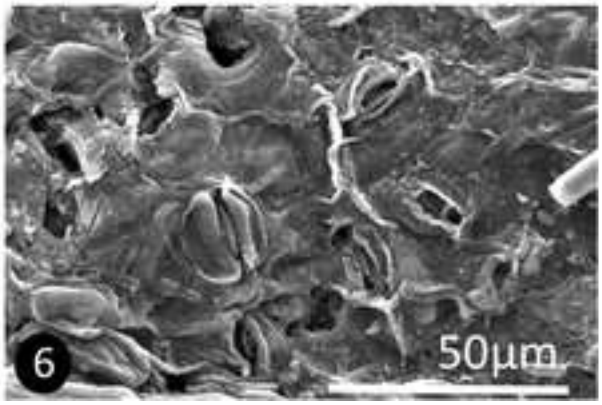
Plate VI



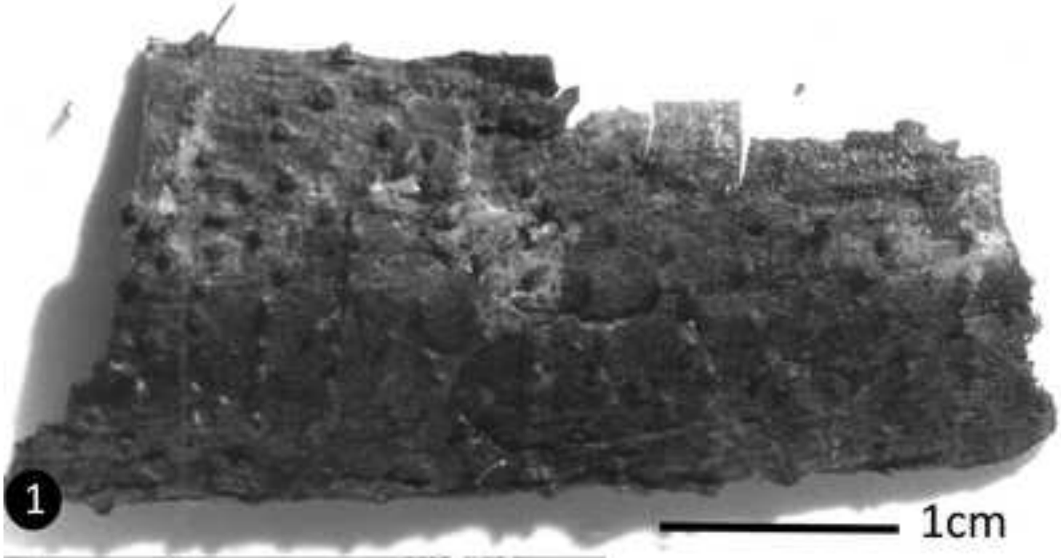


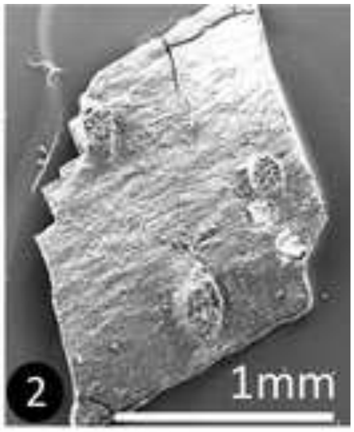


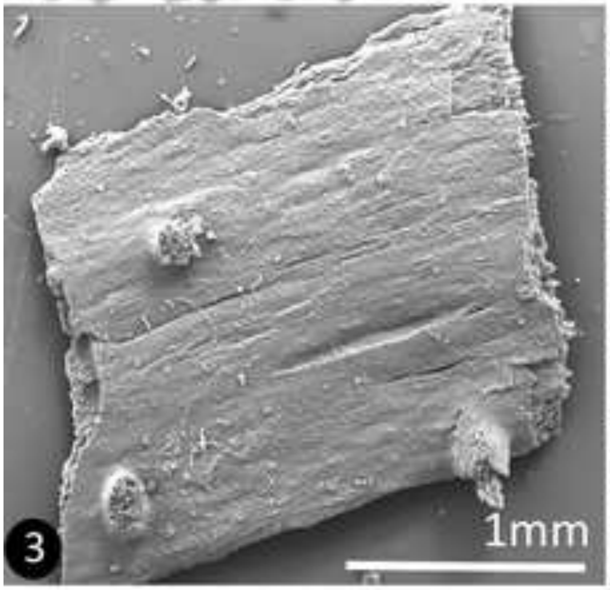


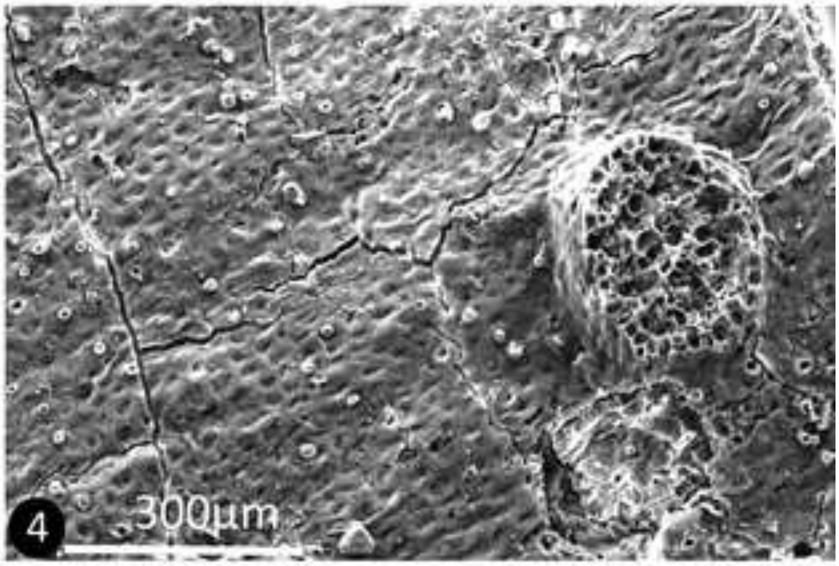


# Plate VII









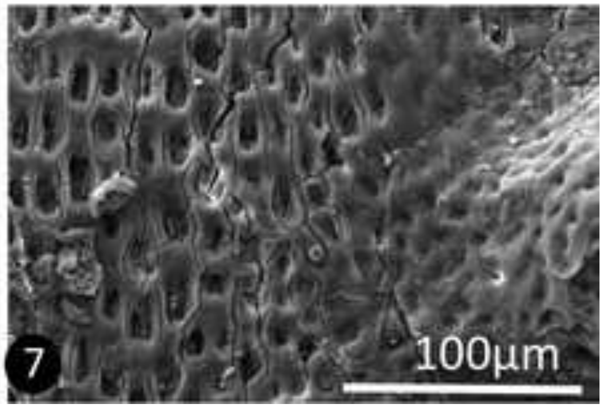


Plate VIII

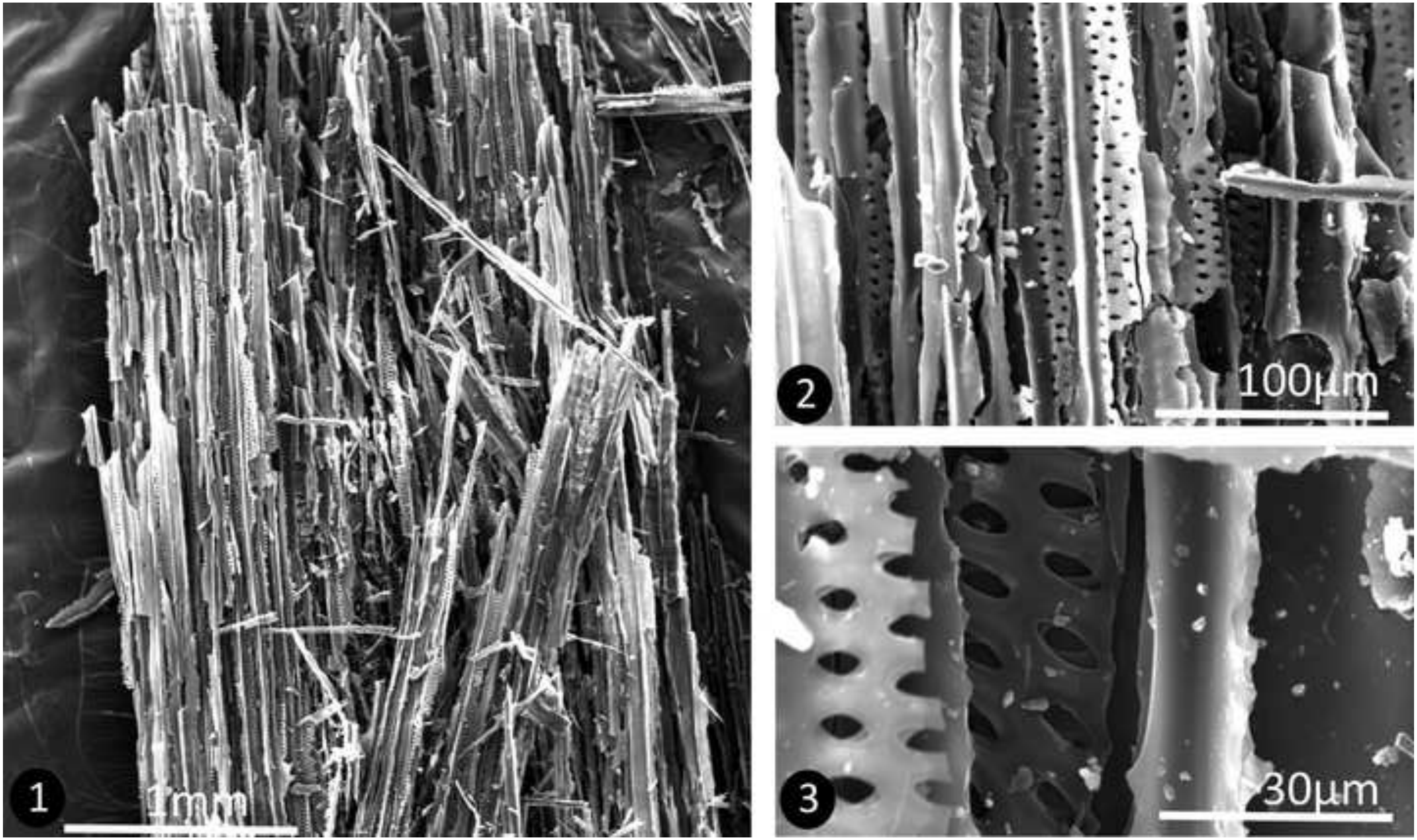
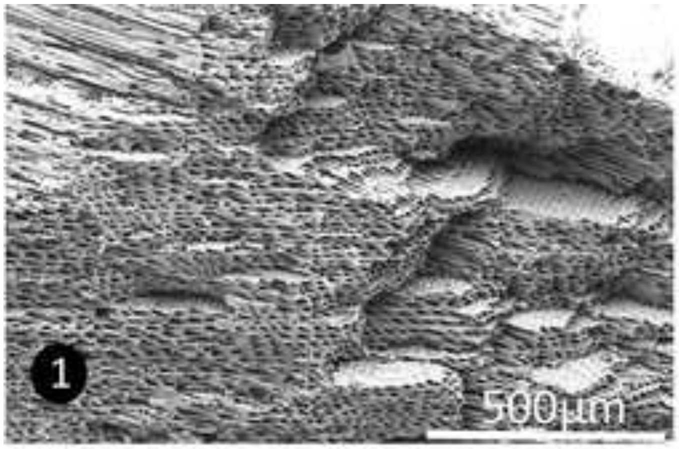
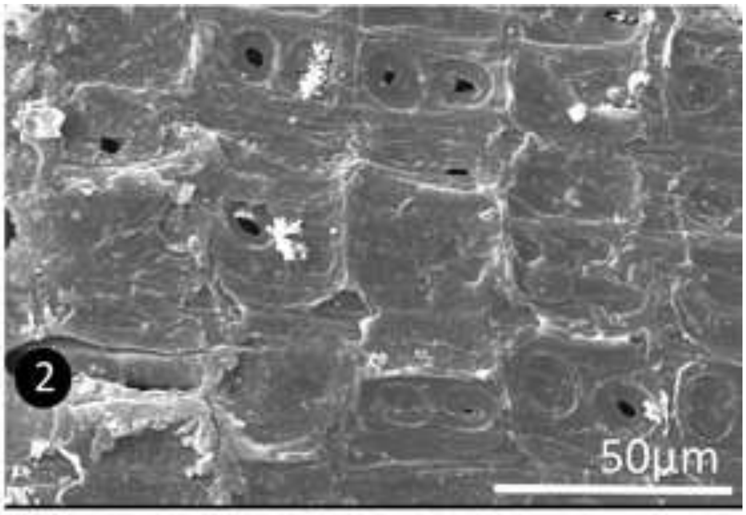
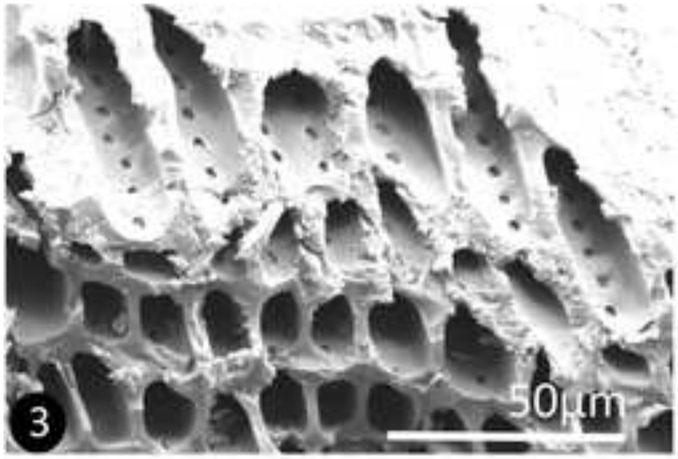
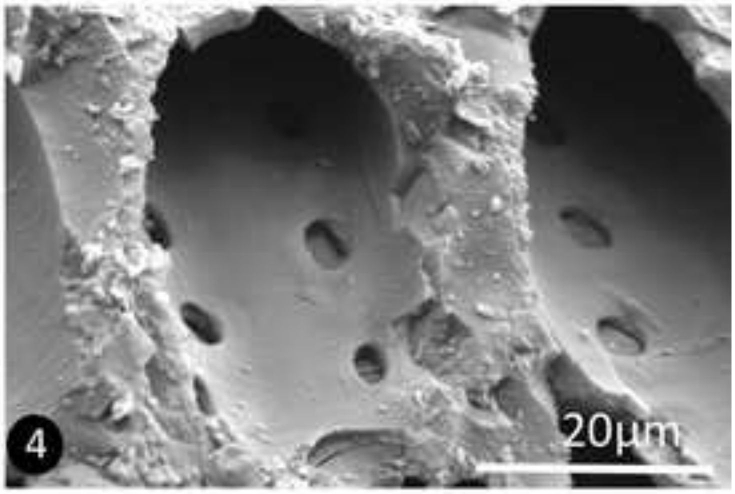


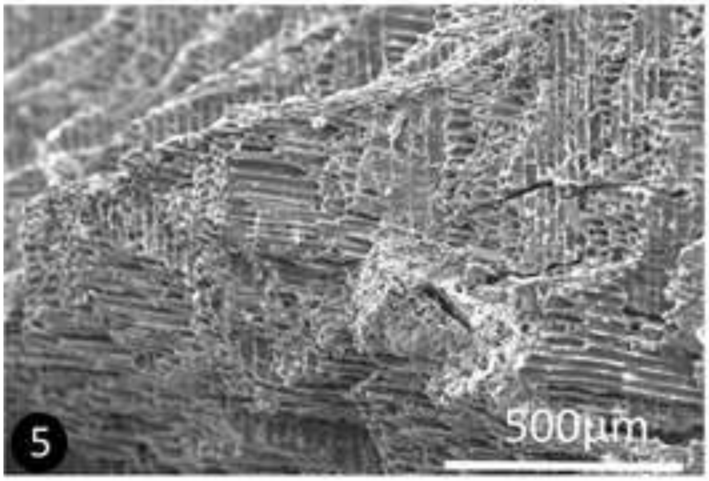
Plate IX











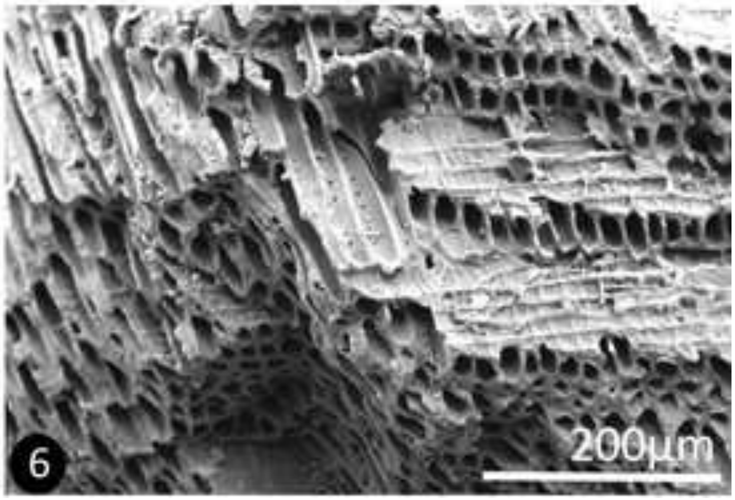


Plate X

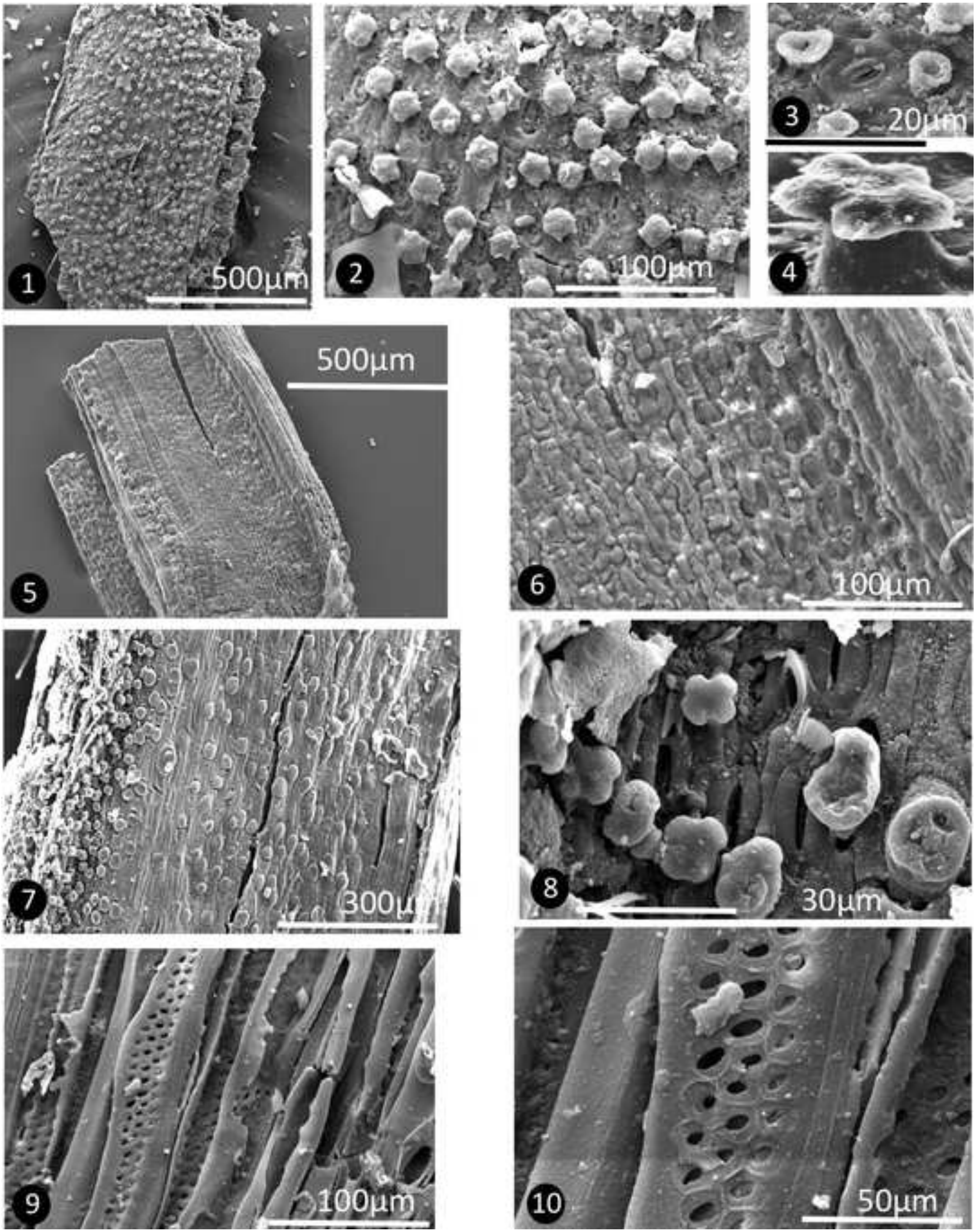

1
500µm
2
100µm
3
20µm
4
5
500µm
6
100µm
7
300µ
8
30µm
9
100µm
10
50µm

Plate XI