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New Carboniferous (Moscovian) Konzentrat-Lagerstätte (Brymbo Fossil Forest, UK)

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ABSTRACT

The upper Carboniferous (Moscovian) sedimentary sequence exposed within the Brymbo Fossil Forest (BFF) Special Site of Scientific Interest (SSSI) in North Wales, UK represents palaeoenvironments associated with an equatorial coal-forming, umbral rainforest in association with river deltas and meandering river systems.

Results of detailed palaeontological excavations are presented, including stratigraphy of the BFF, geochemical proxies of siderite concretions (where the best-preserved fossils are included sometimes in 3D) and palaeoenvironmental reconstructions.

Several episodes of flooding caused rapid burial of the fossils allowing for their renowned preservation, with two endemic species identified: the crustacean *Pygocephalus brymboensis* and the fern *Zeilleria fosterai* helping to update our understanding of the palaeocology of the area. Here we show that the BFF deposit, due to the large number of *in-situ* fossilised plants (300+), the abundance of fossil-bearing siderite concretions (5000+ to date) and the swathes of plants preserved as carbon adpressions is a Konzentrat Lagerstätte deposit, adding much needed detail to the palaeoecology of the region during the upper Carboniferous.

INTRODUCCION

Brymbo Fossil Forest

The Late Carboniferous (Moscovian) sedimentary sequence (315-307 million years old) exposed at Brymbo, North Wales (UK) represents a fragment of the Carboniferous palaeoenvironments when the region was close to the equator with hot, watery, humid, conditions akin to a tropical rainforest in association with river deltas and meandering river environments.

The Brymbo Fossil Forest (BFF) site is part of the Denbighshire Coal Basin (**Figure 1a and Figure 1b**). Records of mineral extraction and associated industries are recorded in the area as early as the 1600s. Metallurgical industry evolved in Brymbo resulting in the area becoming world-famous for producing high-quality steel until 1990, when the site was closed due to economic and political pressures at the time. The subsequent local economic devastation resulted in a loss of approximately 1,125 jobs.

During reclamation work of the old steelworks site in 2005 (**Figure 2a**) a sequence of mainly terrestrial Late Carboniferous sediments was uncovered (~14 meters thick), including mudstones, siltstones, sandstones and seat earths in between two coal seams: the *Crank* and the *Two Yard (Hollin)*. Initial exploration of the sediments (in 2001-2005 [1–3] between the coal seams revealed about 20 very well-preserved, stumps of arborescent Lycopods in growth position (**Figure 2b**) and numerous *in-situ* *Calamites* (horse tails) [4], together with other vegetation, including the ferns *Neuropteris*, *Karinopteris* and *Zeilleria*.

In a rare instance of collaboration between a landowner and geo-conservationists, the national and international palaeontological importance of the site was recognised [1,2,5,6]. It is included in the UK's network of Geological Conservation Review (GCR) sites and is protected by law as a site of Special Scientific Interest (SSSI) since 2008. It is now under the custodianship of the Brymbo Heritage Trust.

After several years working to obtain funding to secure and protect the site with the effort of many invested parties, including local people, ex-steelworkers, volunteers and scientists led by the Brymbo Heritage Trust, the larger site managed to obtain substantial funding (~ 10 million pounds) from several organizations in 2024. These include the National Lottery Heritage Fund, Natural Resources Wales and the Welsh Government.

This funding has helped establish *Stori Brymbo*, a new re-generational tourist attraction celebrating the industrial, social and natural history of the area. Part of the attraction includes a self-contained excavation building covering a part of the fossil forest SSSI allowing the preservation and study of the site. The BFF has already established itself as a centre for earth science research [6–8] and has become both an integral part of the cultural heritage of the area and is appreciated by both the local and scientific communities.

The building protecting the Carboniferous sedimentary sequence (**Figure 3a and Figure 3b**) was completed in spring 2025. This is the only palaeontological site in the UK where continuous excavation is happening year-round and where the public can visit, observe and interact with the palaeontological excavations happening in real time.

The BFF team has developed a new model of excavation and participation involving both local people of all ages and abilities, as well as national and international earth science students at all levels of education.

There are currently two salaried staff running the BFF project; a full-time palaeobiologist as Fossil Forest Coordinator and a full-time intern as part of a locally funded career advancement programme. The remainder of the team includes:

1. **Members of the public interested in natural history.** These volunteers receive training in site excavation techniques, preparation and conservation of fossils, taxonomy and archiving (~30 people).

2. **Members of the public that run the BFF guided tours**, three times a week, since Easter 2025, to explain the site and its significance (~8 people).
3. **University students** who get specialist training on excavation techniques, preparation and consolidation of fossils, classification and organization of fossil archives. Over **200** students from **18** national and international universities have participated in the excavations since 2025.
4. **Research students** are now working on research topics from the site to develop their undergraduate dissertations, master's theses and there has been one successful PhD student who graduated in 2025 [7].
5. **Kids Fossil Forest Club** that gives the opportunity to children from six years of age to have hands on educational experiences with Carboniferous fossils from the site.

It is believed that the working model the BFF has developed, is a good example of a modern, successful and self-sustaining palaeontological excavation that can be replicated in many other nationally and internationally important sites.

The current project aims to excavate and conserve as many *in-situ* Carboniferous fossils as possible and to develop the site as a self-sustaining educational, research and visitor (geoheritage) destination.

The Fossil Forest building has also allowed the detailed study of the Late Carboniferous sequence in 3D detail, including the study of the stratigraphy, spatial distribution of fossils *in situ*, sediment-fossil interactions, palaeobiology and palaeoenvironmental reconstructions.

In this paper it is presented an overview of the current research findings.

99 **Brymbo Palaeogeography and Stratigraphy**

100 During the Late Carboniferous Period the UK, and by extension, Brymbo, was close
 101 to the Equator and covered mostly by dense tropical rainforests. The dominant floral
 102 components of this relatively new ecosystem included the giant arborescent lycophytes (e.g.
 103 *Lepidodendron* [4, 5]), bamboo-like *Calamites* and a multitude of pteridosperms. The faunal
 104 content of the forests, swamps and channels in these systems included amphibian tetrapods,
 105 sarcopterygiid and actinopterygiid fish, early reptilian amniotes and an impressively diverse
 106 array of invertebrates [9]. Some reached gigantic proportions, like griffinflies (*Meganeura*
 107 with 2 metre wing spans) and myriapods (*Arthropleura*, 2.5 metres long,) due perhaps to the
 108 abundance of oxygen in the atmosphere (25-30%), although this idea has been contested
 109 recently [10].

110 The Late Carboniferous saw the emergence of the supercontinent Pangea. The
 111 equatorial tropics appear to have had a hot, wet, seasonless climate rather than arid, desert
 112 conditions. There are several lines of evidence for this including the limited development of
 113 tree rings and the build-up of thick coal-forming peats, which suggests very high rainfall
 114 levels at the time when the earth was rotating faster, with 22 hours per day and 400 days per
 115 year [11].

116 The sequence of sediments exposed at the BFF represent one single terrestrial cycle of
 117 sedimentation (cyclothem) produced during the Late Carboniferous (Moscovian, 315-307
 118 million years ago), **Figure 4**.

119 The cyclicity of sedimentation observed at the time is interpreted to be associated
 120 with changes in sea-level, with a substantial ice cap in the south pole that melted at times. A
 121 total of 8 coal seams and associated terrestrial sediments (cyclothem) have been historically
 122 recorded at the site. They are from the oldest to the youngest: Little Coal, Main Coal, Black
 123 Bed Coal, Brassy Coal, Crank Coal, Two Yard Coal, Powell Coal and Drowsel Coal (some

illustrated in **Figure 2a**). The BFF sequence was located at the southern border of the Pennine Coal Basin and north of the Wales- Brabant High and is condensed in comparison with thicker sediment sequences in the central parts of the Pennine Basin in Derbyshire, UK. The relative paucity of marine bands in this part of the Denbighshire coalfield and geochemical evidence from studies of the BFF cyclothem [7] indicate that the sequence may represent an ecosystem further inland than most other temporally and environmentally comparable sites.

BFF Siderite Concretions:

There is an abundance of siderite concretions in the sediments from Brymbo and the best-preserved fossils are found within them. Carbonate concretions are common in sedimentary rocks of all ages, especially sandstones and mudstones, where they appear as hard, ovoid bodies of sediments that protrude from outcrops. Siderite concretions are made of primarily siderite (FeCO_3), an iron carbonate. Contemporaneous sites to BFF such as Mazon Creek Lagerstätte (Illinois, USA [12]) and the Coseley Lagerstätte (West Midlands, UK [13]) have been subject to intense palaeontological study but the formation of siderite concretions at these sites is far from understood. Although fossils are often found well preserved at the centres of mudstone-hosted concretions, less attention is usually paid as to why this preservation occurs.

The study of concretions can provide an insight into the diagenetic history and palaeoenvironment of a geological site, indicating for example: microbial activity, decay, compaction and groundwater conditions [14].

Siderite concretions are abundant in Brymbo and are characterized by their mineral composition and unique textures, potentially offering valuable insights into the diagenetic processes that have shaped the BFF sedimentary sequence. Study of the Brymbo siderite concretions by Hughes [7] discovered more details about the preservation processes and

therefore the fossil potential of the site along with a detailed analysis of the sedimentation and burial history. The major findings of this research are presented here.

Siderite Concretion Formation

The formation of siderite is more complex and potentially more prolonged than that of calcite. Calcite concretions, very common in marine sediments, usually form via concentric growth, from the inside/core outwards. Siderites in contrast, usually appear to form via pervasive growth, where the entire concretion area forms simultaneously, which often results in a zoned texture within the individual siderite crystals. This zoning means that each crystal may be chemically/isotopically zoned itself and could therefore be representing differing pore water/environmental conditions [15] making environmental interpretations more challenging.

The siderite concretions at BFF site have strong differences in origin depending on their lithology:

a) Mudstones/Siltstones layers: Very abundant, fossil rich siderite concretions followed the stratification and have excellent fossil preservation as adpressions with coal films or in some cases with 3D preservation of fossils associated with kaolinite. All the fossil fauna at the site has been found in these layers, sometimes preserved in 3D.

b) Sandstone layers: Siderite concretions are less abundant here and associated with the two main systems of fracture orientations found at the site and associated with “sausage roll” structures (Figure 5). Presence of fossils in these concretions is rare and they are mainly Calamites. There are also some very flattened nodules in these units, which are less likely to have fossil preservation.

RESULTS AND DISCUSSION

Stratigraphy

Four detailed stratigraphic sections are shown (a, b, c, d), measured, described and surveyed at the site with a total station (**Figure 6**). They highlight the lateral variability of the clastic deposits, location of fossils (some *in-situ*, some transported), position of river channels and interactions between fossil plants and sediments. The location of the four stratigraphic sections is shown in **Figure 7a**, a QGIS location map showing the distribution of *in situ* arborescent lycopod stumps, *Calamites*, which are very abundant in the upper sandstone layers and the abundant siderite concretions present in some sediment layers at the site.

A general composite stratigraphy column for the BFF is presented in **Figure 8**, including the location of different types of fossils found at the site, some *autochthonous* (trans-stratigraphic fossils) and some *pseudo-allochthonous* locally transported by flooding events of increasing severity. A description of each sediment layer is included in **Table 1**.

The BFF terrestrial cyclothem inside the building includes about 14 metres of clastic deposits in between two Coal seams, the Crank and the Two Yard (See Figure 8 and Table 1).

The lower part of the sequence consists of a seat earth (palaeosol) with *Stigmarian*-type rootlets of lycophytes. This is overlain by 0.8 m of Crank Coal seam. This layer has been mined since at least the 1600s. Mining adits and pillars have been discovered at the bottom of the BFF excavation area that do not appear in any historical records, so they are likely to be at least pre-Victorian in age.

Above the coal there is a coarsening upwards sequence that starts with laminated carbonaceous clays/mudstones, the lowest part containing a thin ironstone layer. The clays/mudstones are very fossiliferous with an abundance of fossil plants including detached pteridosperm pinna (eg. *Pariapteris pseudogigantia*) together with plant debris. Rare fauna includes isolated blattoid wings, conchostracan crustacea and microconchida.

About 1.30 m above the coal layer, about 20 arborescent lycopods stumps (*Lepidodendron*) have been found in growth position in a thin coal parting (1-2 cm thick) at this level. The arborescent stumps range up to 1.5 metres in diameter and 2.6 metres in height. The best, most complete example was excavated in 2008 and is now part of the collections at the National Museum of Wales, Cardiff, UK. [19].

Calamites stems in growth position first appear towards the top of the silty mudstone layers associated with laterally discontinuous sandstone lenses that represent the banks of meandering rivers with large numbers occurring as *in situ* vertical casts.

Ferns like the filicopsid *Zeilleria fosteri* (endemic to Brymbo [5]), the arborescent pteridosperm *Neuropteris* and the lianescent pteridosperm *Karinopteris* also occur in the silty mudstones and are irregularly scattered, often as tangled mats of vegetation.

Arguably the best-preserved fossil specimens (plants and animals) are recovered from the abundant siderite concretions (ironstones), which occur in low concentrations sporadically within some strata but in very high concentrations as irregular bands in the silty mudstones, following the stratification in layers: B1, B2, B3 and B4. (Figure 8). The fossils are well preserved either in 3D or as adpressions of black coal films. Between 50%-60% of the 5,000+ concretions that have been opened to date (either by mechanical or freeze-thaw methods) have yielded well-preserved fossil material.

After the mudstone layers, the sequence starts to coarsen to siltstones cut with small channels infilled with fine sandstone. There are many megaspores and lycophyte cones, transported by water.

In general, the siltstones show fissile fracturing associated with brittle deformation, sometimes with the presence of “star” fractures radiating from buried *Stigmaria* roots (**Figure 9**).

This unit is overlain by a grey, fine grained, massive sandstone, up to 1.5 meter thick in channel form. The *in situ* lycophyte stumps continue into this unit but rarely above it. *Calamites* are found in abundance, either in vertical growth position, inclined or flattened/imbricated following the direction of rapid water flow. The top sandstone unit has siderite concretions, but their position is very different with respect to the stratification, in contrast with the siderite concretions found in the mudstones. They are surrounded by mudstone material, that gives the impression of a “sausage roll” of sandstone surrounded by very fine blue mudstone (**Figure 5**).

The remaining 1.5 meters to the base of the Two-Yard Coal seam is a sequence of seat earths (palaeosols) with medium grain size sandstones interbedded with mudstones. *Stigmaria* roots are numerous, with 1 example reaching up to 8 meters in length.

Discussion of Stratigraphy Results

The Brymbo cyclothem represents inundations of increasing fluvial energy, that first transforms the area from forest to swamp, then a meandering river system as part of a sandy floodplain. The changes in flora and fauna reflect this changing ecosystem.

Starting with initial minor flooding into the forest, which deposited mudstones, Units B1, B2, B3 and B4. This transitions towards a bog-like mire that removed mid-canopy tree-like pteridosperms and favoured arborescent lycopods, scrambling *Sphenophyllum* and eventually with *Calamites* horsetails in unit B4.

Increasing severity of floods culminated in a series (3–5) of flooding ‘pulses’ that covered the swamp in coarser grained sands, Units B5 and B6. These infilled the lycophyte and *Calamites* stumps with sand (producing pith casts) and generated channel deposits with eroded bases, that prograde laterally to the north-east. These flooded sandy banks became hosts to a monodominant *Calamites* population in thickets, with minor presence of ferns fragments around them.

The flooding eventually subsided and towards the top of the sequence a new seat earth developed as a silty layer with Stigmarian root-systems. This seat earth becomes the new forest floor and allows the succession from *Calamites*-dominated sandy floodplain back to a stable tropical rain forested environment that subsequently results in the upper-bounding Two-Yard Coal seam.

The BFF sequence is interpreted as a traditional coal-forming forest but slightly farther inland than other similar UK Carboniferous Forest sites [5]. Marine bands are relatively infrequent in this part of the Denbighshire coalfield, and geochemical studies [7] support a lack of marine influence in the exposed Brymbo studied section.

Fossil material is abundant throughout the sequence, and the BFF site is famous for its large lycopod stumps with associated root systems, see **Figure 2b** [3,19] and large thickets of *in-situ Calamites* (**Figure 3b**).

The BFF sedimentary sequence has a general dip between (12-14 °) towards the SE and has evidence of two different styles of deformation structures derived from the Variscan Orogeny depending on the source sediment: a) mudstones or b) sandstones.

1. In the mudstones/siltstones, brittle deformation is evident with star fractures in layers B1, B2, B3 and B4. **Figure 8**.
2. In contrast, ductile deformation is evident in the sandstone unit, layer B6 with small gentle folds and sandy stringers that look like “sausage rolls” (**Figure 5**). These stringers are formed by vertical and horizontal movement of the underlying blue mudstone in two injection phases associated with soft sediment deformation. These top sandstones have a well-defined system of fractures, infilled by fine blue mudstones. The fractures on the top sandstone unit have near vertical dips between 70° to 89°, with strikes between 279° to 346° and are all infilled by fine blue mudstones.

273 Fossil Preservation from the BFF

274 There are three major fossil preservation pathways observed within the BFF:

- 275 1. The most common are the *carbon adpressions* (a term to describe partially
 276 compressed plant matter with a carbon film [20]). Adpressed fossils occur in most of
 277 the strata but most commonly in finer grained mudstones and clays toward the bottom
 278 of the sequence, increasing in concentration downward until fossil material quantity
 279 exceeds inorganic matrix and the strata grades into coal. The most common adpressed
 280 fossils are isolated pteridospem pinnules, isolated lycopod needles (*Cyperites*) and
 281 lycopod 'leafy shoots' of the form-genera *Lepidophylloides* (small segments of
 282 branch).
- 283 2. The second pathway is for the fossil to be encased in a concretion. Thousands of
 284 siderite concretions, composed of siderite, an iron carbonate mineral (FeCO_3) have
 285 been discovered, logged and processed from the BFF strata (Figure 7c). These
 286 concretions are a complex geological phenomenon resulting from a specific set of
 287 sedimentary circumstances. In environments where the groundwater is iron-rich (such
 288 as these wet, terrestrial, tropical rainforests) and finer sediment deposition prevails,
 289 dead organic matter can be sealed in oxygen poor strata that promotes decay via
 290 anaerobic bacteria. The production of methane and carbon dioxide as decay waste
 291 products, creates a highly localized chemical microenvironment that decreases acidity
 292 and promotes the attraction of iron and carbonate ions to form siderite. The siderite
 293 crystalises around the fossil protecting it. This process happens before ultimate
 294 compaction of the surrounding sediment offering some protection against compaction
 295 to the fossil inside. While around 60% of the concretions processed on site contain
 296 macrofossil material of varying quality, some 40% appear barren. This may be the
 297 result of poorly understood spontaneous formation of siderite concretions or that the

concretion may nucleate around concentrations of microscopic faecal pellets or other hard to visualise organic material, Unsurprisingly, for a fossil forest, most of the siderite concretion fossils are those of plant remains, mainly *Cyperites* and other lycopod form genera but also, very occasionally, well preserved animal remains are recovered from them including the crustacean *Pygocephalus brymboensis* [8], the xiphosuran *Euproops* sp., the sarcopterygian *Strepsodus* sp. and diplopod *Myriacanthepestes* sp.

3. The least common preservation pathway within the strata is the cast and mould preservation of *in situ* plants by catastrophic inundation. Hundreds of ‘pith-casts’ of standing *Calamites* [21,22] dot the surface of the site which represents the top sandstones deposited by inundation (Figure 8, units B5-6). These fossils form after a standing plant is partially buried in sediment, dies, then decays leaving a void. This void is then filled by another inundation of sediment (fine sands) resulting in a cast and mould.

The BFF is very fossiliferous, and some representative examples are shown in **Figure 10a (plants) and Figure 10b (animals)**. They include the endemic species found at Brymbo: the crustacean *Pygocephalus brymboensis* [8] and the fern *Zeilleria Fosteri* [5].

Due to the large number (300+) of *in-situ* fossilised plants, the abundance of fossil-bearing siderite concretions (5000+ to date) sometimes with 3D detail and the swathes of plants preserved as carbon adpressions, the BFF deposit is classified here as a new Konzentrat Lagerstätte deposit [12,13,16,17,18] due to the exceptionally large number of well-preserved fossils and the palaeontological/palaeoenvironmental information that can be obtained from their study.

Siderite Concretions Results and Discussion

A total of 25 hand specimen samples were studied in cut section, showing varied textures; some show evidence of bioturbation while others are more homogenous. It was initially clear that two colours of siderite were present in the samples and isotopic drill sampling aimed to cover these textures and different coloured sediment. The darker coloured areas of concretion turned out to be rich in Fe-rich siderite, whereas the lighter areas had a higher quantity of Mg-rich siderite. Only 2 of the 25 concretions studied showed textures that could be indicative of bioturbation (mostly seen in unusual mixing of siderite colours due to grain disturbances) (Figure 11 D). Most concretions preserved sedimentary laminations or were made up of fine-grained silt (Figure 11, A, C) and were cemented by microcrystalline siderite. All concretions had very fine detrital organic grains included, probably fragments of plant fossil material (Figure 11, B).

The concretions did not present concentric rings of growth around a fossil, instead they show a homogeneous texture through the whole concretion, preserving laminations and bioturbation features, with the fossil in the middle of the concretion. Many had orange oxidised external rims (**Figure 11**).

In thin section, all nodules consist of mostly fine-grained quartz with minor aluminosilicate grains with a microcrystalline, sometimes zoned siderite cement. Most concretions show a consistent 'blotchy' texture of microcrystalline masses of apparently porous siderite, sometimes stratified/laminated and rectangular in shape (**Figure 12**), and other times chaotic and turbulent (**Figure 13**). These are often associated with the only occurrences of pyrite within the nodules.

These textures seem to displace any quartz or other grains suggesting they were at least a semi-solid structure prior to burial. These textures seem to have induced early microenvironments of sulphate reduction, producing bisulfide and in turn causing the early precipitation of pyrite during the very first stages of diagenesis once the sub-surface

environment had become anoxic. This early pyrite formation will have taken any sulphate out of the system before siderite formation began. A suggestion for these textures in the BFF samples would be that these represent faecal pellets or replaced phytoclasts. Such structures, being nearly completely Fe-rich siderite are likely a key factor in the growth of early siderite concretionary areas. These structures, being rich in organic matter would have then been partly consumed/enveloped by methanogenic archaea, once buried a little deeper, creating bicarbonate alkaline conditions for the growth of siderite and the near full replacement and preservation of these pellets by early forming siderite.

Both the clay mineral/biofilm coated plant fragments and the ‘pellets’ would have provided nucleation points for the growth of siderite cement between the quartz grains of the host sediment. The host sediments being siltstone and sandstone means that reasonably high initial porosity allowed good migration of fluids and the components required for the bacterial production of bicarbonate and precipitation of siderite despite the bulk organic carbon content of the host sediments being relatively low.

The formation of the peat/coal layer above the BFF sediments and the newly formed Crank Coal below, could have provided the large amounts of organic carbon required for methanogenesis through leaching into the pore-rich sediments. Large fragments of plants and animals offered the most common nucleation points, and all nodules appear to have formed via pervasive growth.

The rate of growth of the skeletal network of the early cementing siderite during compaction must have been quick enough to prevent entire crushing of the plant structure, preserving the encased fossils in 3D. During sampling of the sawn concretions, no obvious patterns were observed in the spread of the two phases of siderite across each concretion, again suggesting pervasive growth where the entire volume of the concretion was already set

by precipitation of Fe-rich siderite and leaving enough pore space to allow for later infilling by Mg-rich siderite.

The sediments must be anoxic for siderite to form as iron is required in solution, in its reduced state, Fe (II). If combined with oxygen, it would precipitate out of solution as ferric iron, Fe (III). The origin of ferrous iron in the sediments could be from the coal layer below the fossil forest sediments which may have formed bog iron during initial peat formation.

The study of thin sections showed the presence of two chemically distinct phases of siderite, one which made up the bulk of the cement and the entirety of the faecal pellets (a near 'pure' siderite AKA Fe-rich siderite) and one, Mg-rich type which appeared to fill in residual porosity post cementation (Mg-rich siderite). This second phase of siderite was also confirmed via bulk XRD analysis which showed 2 distinct phases, separated by their differing Mg content. Quantitative EDAX also showed some sector zoning within the large crystals of Mg-rich siderite, with the quantity of Mg generally increasing towards the outside of the crystal (**Figure 14**).

Stable carbon and oxygen isotopic data from all the sampled siderite nodules shows a positive covariant trend between around -1‰ to 11.5‰ for $\delta^{13}\text{C}$ and between around -9.2‰ to -6.3‰ for $\delta^{18}\text{O}$. It was found that a mixing effect of the two distinct siderite phases caused the observed trend as they were formed under different conditions with different processes fractionating the isotopic ratios (**Figure 15**). These end-member phases were then estimated via extrapolations of the mixing trend to determine their true isotopic values (**Table 2**, see [7]).

Siderite Concretions Conclusions

Geochemical analysis showed that the abundant BFF siderite concretions have a complex formation history. Further investigation proved that the usefulness of such

concretions for making environmental interpretations is limited and fraught with issues surrounding the complexity of their origins. Analysis of the siderite concretions allows for a greater understanding of the diagenesis and preservation of the fossils at BFF and confirmed the environment was supplied with purely meteoric/fresh water.

The BFF concretions were first formed, via pervasive growth, by a skeletal network of a near pure siderite (referred here as Fe-rich siderite) which created each concretion's entire volume. This phase of siderite must have precipitated early on during compaction/diagenesis in meteoric water at near surface temperatures, preserving the 3D structure of fossils and yielding isotopic values indicative of a methanogenic environment.

A later phase of siderite (Mg-rich siderite) infilled the remaining pore space, which was maintained during compaction by decayed plant fragments/material and the silty/fine sand grain size of the sediments. Mg-rich siderite gave isotopic values indicative of a thermal decarboxylation source and carried a geochemical signature that suggests it was precipitated from a significantly different water source at higher temperatures and at a greater depth. The mixing of these siderites created an isotopic trend that may otherwise have been interpreted as a brackish or evaporative environment, which is not the case.

High magnification microscopy shows evidence of chemical zoning within both phases of siderite which would be too small scale to sample and test. Only by calculating the percentage wt. fraction estimates of the two discovered phases can we gain the true isotopic end member values and therefore make any reliable interpretations about the true precipitation conditions.

The geochemical similarity of the BFF concretions to those of the Coseley Lagerstätte [23,24] suggests the plausibility of future discovery of soft bodied animal fossils at Brymbo which has big implications for the future and impact of the BFF research project.

Indeed, already there have been animal fossils found in siderite concretions in the mudstones/siltstones with very good preservation (*Pygocephalus brymbonensis*, *Euproops sp.* *Strepsodus sp.* and *Myriacanthepestes sp.*) Analysis of the Brymbo siderites also helps to understand how some of the plant fossils were exceptionally well preserved within concretions, due to early forming, biologically mediated, clay mineral (kaolinite) coatings acting as early siderite nucleation points.

The complex burial history displayed by the analysis of the siderite concretions yielded limited palaeoenvironmental data but has significant implications for further ecological research using them and for our understanding of the formation and diagenesis of the BFF sediment package.

New Methods for Old Problems: 3D (μ -CT) Scanning of a *Lepidodendron* Branch.

Examples of new technologies used in the study of fossils include the use of μ -CT, because it is a non-destructive technique, keeping the fossil perfectly intact.

μ -CT has been used at the BFF, in a similar method to Herrera *et al.* [25] where a fragment of a Carboniferous lycopod branch, *Lepidodendron*, has been removed digitally from a siderite concretion. The results of this scan, represents the first digital 3D reconstruction of a *Lepidodendron* since its original description by von Šternberg [4]. The 3D digital image is presented in **Figure 16**.

Description: The 79mm bifurcating branch has approximately 129 leaf cushions which are fusiform/rhomboidal in shape, taller than wide. They have smooth lateral sides, widest where they meet the prominent lateral lines, which merge into the edge of the leaf lamina. Keels are present on all the leaf cushions, but they vary from smooth to plicated.

The microphyll leaves protrude from the leaf cushions at a 90° angle and are long and thin, depending on the position along the branch the leaf shape changes. Leaves found toward the proximal end of the branch dip down then curve back up in an S-shape, whereas leaves

toward the distal end curve straight up, never dipping down in the first place. The most interesting feature revealed by this scan are small protrusions found just above the leaf lamina on the adaxial face of the leaf cushions. These protrusions are located where the ligule pit would be found.

On average these protrusions extend 0.7mm from the leaf cushions surface. It is important to note the frequency of the protrusion and as with the leaf shape, there is a change between the distal and proximal ends. Almost all the proximal leaf cushions have protrusions on the adaxial leaf cushion surface compared to sparse protrusions found on the more distal leaf cushions, particularly after bifurcation of the branch.

The identity of these protrusions remains unknown as they have not been previously described. More μ -CT data needs to be collected whilst identifying and comparing these structures in the compressed fossils of *Lepidodendron*. The decreasing frequency of the protrusions whilst travelling up the branch (if they are found to be part of the plants morphology) may allude to some form of ontogeny in the branches of *Lepidodendron*. A higher frequency of protrusions could mean an older branch or possibly a new sub-species.

The application of μ -CT 3D scanning techniques at the BFF has the potential in the future to provide a wealth of new data on the internal features of plants and animals present at the site.

Paleoenvironmental Reconstructions of the Brymbo Fossil Forest

Two strata-specific palaeoenvironmental reconstructions are provided here (**Figure 17 and Figure 18**) using cross-disciplinary work from geological, palaeobotanical and geochemical data. Preservation styles and the 3D spatial relationships of fossils surveyed on site have been specifically used.

The reconstructions represent a snapshot within specific sedimentary packages. The choice was made to only represent flora and fauna found within the package. In this way it is

possible to present a highly informed, but (due to the random nature of taphonomy) likely incomplete, reconstruction.

These two reconstructions represent data collected and interpretations postulated by the many excavators that have worked at and researched the site. These illustrations provide a view into the fast-evolving palaeoenvironments preserved within the stratigraphy at BFF. They represent some of first tropical rainforest ecosystems to be developed during the upper Carboniferous.

Mudstone/Siltstone deposits (Figures 17a and 17b): These show plant and animal fossils assemblages, for sedimentary units: **B3, B4, (Figure 8)** which are associated with gentle, low energy, flooding of a lagoon-like environment, with multiple sequences of sediment input, evidenced through fine laminations.

Sandstone deposits (Figures 18a and 18b): These show plant fossil assemblages, for sedimentary units: **B5, B6**, which are associated with higher energy flooding associated with meandering river channels.

CONCLUSIONS

The exploitation of Carboniferous Coal basins fuelled the industrial revolution in the UK. Countless industrial sites were created, exploited and left abandoned throughout the XIX and XX Centuries. Despite the consensus being that the coal measures sequences of the UK have been exhaustively studied and are well understood, the BFF highlights that paleontologically this is not entirely true. Historically, most of the knowledge concerning the fossils of the Carboniferous coal measures has been derived from *non-in situ* sources, such as spoil tips from mining operations, without stratigraphic context [8]. At Brymbo, this is not the case.

The Stori Brymbo visitor attraction and the BFF is an excellent example of the integration of industrial and natural history that can now be explored and studied in much

more detail. There is still a wealth of palaeoecological information that can be obtained with the application of new technologies (surveying, geochemical proxies, 3D imaging) to the site.

The completion of the building covering & protecting the Brymbo sedimentary sequence has allowed the continued excavation and study of the palaeontological site in unprecedented 3D detail that has transformed our understanding of the significance of the Upper Carboniferous terrestrial sequence in the UK and globally.

The Brymbo cyclothem sequence is now better understood, together with its sediments, sedimentary structures, fossils and palaeoenvironments associated with its equatorial position during the Late Carboniferous (Moscovian), in a dynamic river delta environment.

New endemic species of animals (*Pygocephalus brymbonensis*) and plants (*Zeilleria fosteri*) have been discovered *in situ* at the site, allowing a much more detailed picture of their habitats/palaeoecology. This is associated with the rapid environmental changes related to flooding events associated with the melting of ice caps, in repetitive cycles (cyclothem).

Two detailed palaeoenvironmental reconstructions are presented here for the BFF at different times of deposition. It is impossible to try to produce detailed palaeoecological studies without considering if the fossils are *in-situ* or transported in the sedimentary sequence.

The origin of the clastic sequence resulted in the rapid burial of the fossils (plants and animals) which promoted the abundant development of siderite concretions mainly in the mudstones/siltstones units. This was due to diagenetic post-depositional processes that allowed the good preservation of the fossils.

Detailed studies on the siderite concretions that included textural analysis, geochemical studies (XRD, microprobe analysis, isotopic analysis) indicate that they have a complex diagenetic history. There were at least two phases of siderite formation: 1) at the

surface-meteoric water level and 2) a later phase at depth after burial. Due to this knowledge, it is suggested here that their use (currently) as palaeoenvironmental indicators should be taken with extreme caution.

New sedimentary structures have been found and described at the site, including the “sausage roll” siderite concretions in the upper sandstones and the “star fractures” in the siltstones. They point to a complex tectonic history associated with fracturing and deformation after sediment deposition associated with the Variscan Orogeny.

It is proposed that the BFF site is a Konzentrat-Lagerstätte deposit with many well-preserved fossils of plants and animals from the Upper Carboniferous (Moscovian).

METHODS

Concretion Sample Preparation

Twenty-five siderite concretions were selected covering the widest possible range of strata at BFF (**Figure 19, Figure 20**). The distribution of the concretions in the sequence is mostly random within each horizon, although in some layers they were parallel to the stratification. Only a few horizons in the sequence were devoid of concretions. All concretions were sawn in half and polished to observe their textures before selecting analytical sample locations.

XRD Analysis

Randomly oriented samples were prepared by back-loading powders into circular cavity mounts and scanned from 10 to 75°2 θ (0.017°2 θ step interval, 1.85 seconds per step) using Co radiation generated at 45 kV and 40 mA), and a Panalytical X’Pert Pro MPD X-ray diffractometer (Bragg-Brentano reflection geometry) fitted with a primary Ge crystal (K α 1) monochromator.

Resultant diffraction data were transformed via a computer algorithm [26,27]. Following background subtraction, line profiles for key diffraction peaks were fitted. Compositionally dependent integrated mineral intensity factors for the $d_{(10.4)}$ diffraction line (Co $K_{\alpha 1}$), used in this study to estimate the relative proportions of low-Mg and high-Mg siderite phases, were calculated following the procedure of Runnells [28].

Isotopic Studies

Once sawn in half, many concretions showed some form of texture or fabric which guided the location of the sampling points. In most concretions, multiple samples were taken to cover the outside edges and centres of the concretions along with any variations in colour, grain size or mineralogy within them. A small tungsten drill bit was used to collect around 15mg of powdered sample from each location and these samples were then sent to the Stable Isotope Laboratory in Liverpool University for analysis.

Samples were prepared for carbon ($\delta^{13}\text{C}/\delta^{12}\text{C}$) and oxygen ($\delta^{18}\text{O}/\delta^{16}\text{O}$) isotope ratio analysis following the classical manual, ‘sealed vessel’, procedure described by Swart, Burns and Leder [29]. Product CO_2 was recovered under vacuum using standard cryogenic techniques to remove water vapour (at -87°C)

For the purposes of measurement calibration each batch of samples (typically 13 unknowns – new materials to be measured) was accompanied by contiguous preparation of CO_2 from aliquots (3 per batch) of a secondary laboratory reference calcite – LIVM3 (Carrara marble).

Resultant delta values (δ) were corrected for ^{17}O interferences [30,31] and calibrated to the Vienna Pee Dee Belemnite (VPDB) carbon and oxygen isotope reference scales via a one-point procedure using the mean value obtained from replicate within-batch measurement of LIVM3 as a scale anchor.

Microscopy of Concretions

Polished thin sections were made from seven selected siderite concretions. The sections were first observed under normal and cross polarised light to determine which features/textures would be worth further investigation. A JEOL JSM 7001F FEG-SEM with a retractable BSE detector and an Oxford Instruments Ultim-Max EDS detector with AZtec software was used for imaging and chemical compositional analysis. BSEM images were taken to highlight individual grains and the siderite cement surrounding them along with any observable textures and grain relationships. EDS/EDAX was used to create element maps or spectra of individual points which showed siderite with distinctly different chemistries and highlighted the mineralogies of each concretion.

μ-CT scanning of a siderite concretion

A siderite concretion with evidence of having a *Lepidodendron* branch inside was selected. The concretion was placed inside a μ-CT scanner where an emitter passes X-rays through the fossil, some of these rays are absorbed or deflected by the fossil, whilst some pass through the fossil to a detector plate where a 2D image is produced, the more electrons that hit this plate the darker the image. For example, the air around the fossil will come off as pitch black whilst the fossil material appears a shade of grey or white depending on the density of the material. This process is repeated thousands of times to create a series of cross-section images through the fossil in the XYZ axis, the smaller the gaps in between these cross-sections, the higher definition the image.

Then the cross-sections from the XYZ axis are combined creating voxels (3D pixels), converting the fossil into a block of 3D cubes with each cube containing individual density data. Software such as Dragonfly, 3D slicer and AVIZO can be used to segment this data,

593 separating matrix from fossil. This is reliant mostly on a difference in the densities within the
594 sample.

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597 **Data availability**

598 All the data are available on request. The fossil specimens studied are curated and available at
599 the BFF laboratory.

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687 **Tables**

688 **Table 1.** Brymbo Fossil Forest sedimentary units: Description of sediments, structures, fossils
 689 present and palaeoenvironmental interpretations for each sediment unit.

Sedimentary Unit Number	Units Senu Thomas <i>et</i> <i>al.</i> , 2019	Characteristics of Palaeoenvironment sediment units and structures	Flora for each layer	Fauna for each layer
BFF				
B11	Y4	Ironstone, Dense blocky iron-rich 'bricks' with jointing (0.15 m)	Palaeosol, experiencing fluctuating groundwater conditions)	
B10	Y3	Two Yard Coal, black organic rich sediments, layered (1.5 m)	Vegetated swampy floodplain: from mire to peat to coal deposits.	
B9	Y2	Seat earth, light grey mudstone with roots (0.3 m)	Drying up sequence: palaeosol, clay development.	
B8	Y1	Two Yard Coal, black organic sediments (1m).	Vegetated swampy floodplain: From mire to peat to coal deposits.	
B7	C8	Seat earth, light grey fine mudstone, with roots, laminated. (0.3 m)	Fluvial plain: emergent and drying up sequence, palaeosol formation.	Stigmarian rootlets <i>Calamites</i>
B6	C7	Light yellow medium sandstone. Finely layered. Larger channels. Some cross stratification. Many fractures infilled with blue clays with different orientations. Presence of sandy	Major fluvial influence, larger fluvial channels, > 3 meters in diameter, erosional bases cutting into sandstone unit below, drying upwards sequence.	<i>Lepidodendron</i> form genera <i>Calamites</i> <i>Karinopteris</i>

		“sausage concretions”. Iron staining. Abundant <i>Calamites in-situ</i> , some following near vertical fractures. Some <i>Calamites</i> inclined by water current. Lycopod trunk <i>in-</i> <i>situ</i> . (2.10 m thick)			
B5	C6	Buff fine sandstone , in small channels up 2-3 metres diameter, with iron staining. Lots of crushed vegetation at lower contact. <i>Calamites</i> abundant, with some cross stratification (0.8 m thick)	Fluvial channels, cutting into the mudstones below, coarsening upwards sequence.	<i>Lepidodendron</i> form genera <i>Calamites</i> <i>Asterophyllites</i> <i>Karinopteris</i>	
B4	C4/C5	Light grey mudstone interbedded with siltstones, occasional small sand lenses. Abundant fossiliferous siderite concretions following stratification. Ripple marks. Very fossiliferous unit. Fissility fractures: star fractures. Trunks <i>in-situ</i> (<i>Lepidodendron</i>	Flooding units, Several flooding episodes. With shallow lake, fluvial overbank sediments, with occasional sand lenses. Drying and coarsening up sequence from clay to silt to sand lenses.	<i>Asterophyllites</i> <i>Karinopteris</i> <i>Sphenophyllum</i> <i>Lepidodendron</i> form genera <i>Calamites</i>	<i>Pygocephalus</i> <i>Myriacanthorpestes</i> <i>Euproops</i> Palaeodictyoptera

			<i>and Cordiastes</i>), plant adpressions, worm trails.		
B3	C4	Dark grey mudstone, intermittent ironstone beds. Plant adpressions foliage, abundant ferns. Abundant siderite concretions with fossils.	Flooding: Shallow lake, fluvial riverbank, freshwater lake on delta plain.	<i>Paripteris</i> <i>Mariopteris</i> <i>Cordaites</i> <i>Lepidodendron</i> form genera	<i>Strepsodus</i> <i>Actinopterygia</i> Microconchida
B2	C4	Dark grey mudstone, thin layer, with fossils. Siderite concretions.	Flooding: Shallow lake, fluvial riverbank, freshwater lake on delta plain.	<i>Paripteris</i> <i>Neuropteris</i> <i>Lepidodendron</i> form genera	<i>Necmylacris</i> <i>Leaia</i>
C2	C3	Coal stringer, thin organic rich layer (1-2 cm thick).	Vegetated swampy floodplain: from mire to peat to coal deposits.	Coal compressions of <i>Lepidodendron</i> form genera	
B1	C2	Seat earth/Mudstone, thin layer	Palaeosol: Fluvial plain emergent and drying up sequence with palaeosol formation.	Stigmarian rootlets	
C1	C1	Crank Coal, black organic-rich sediments, layered (0.8 m)	Vegetated swampy floodplain: from mire to peat to coal deposits.	Coal compressions of <i>Lepidodendron</i> form genera	
C0	B3	Seat earth below Crank Coal, light grey mudstone with many roots. With <i>in-situ</i> Stigmaria.	Fluvial plain: emergent and drying up sequence, palaeosol formation.	Stigmarian rootlets	

Table 2. Summary of derived end-member geochemical compositions for low-Mg and high-Mg siderite phases. Isotopic values are presented as mean values. Note major differences in isotopic values along with Mg and Fe [7].

Siderite phase	Derived end-member compositions					
	MgCO ₃	CaCO ₃	MnCO ₃	FeCO ₃	d ¹³ C _{VPDB}	d ¹⁸ O _{VPDB}
	(mol %)	(mol %)	(mol %)	(mol %)	(‰)	(‰)
Low-Mg	5.3	1.4	1.6	91.7	+13.2	-5.9
High-Mg	28.3	3.4	1.4	66.9	-7.6	-10.8

Figures

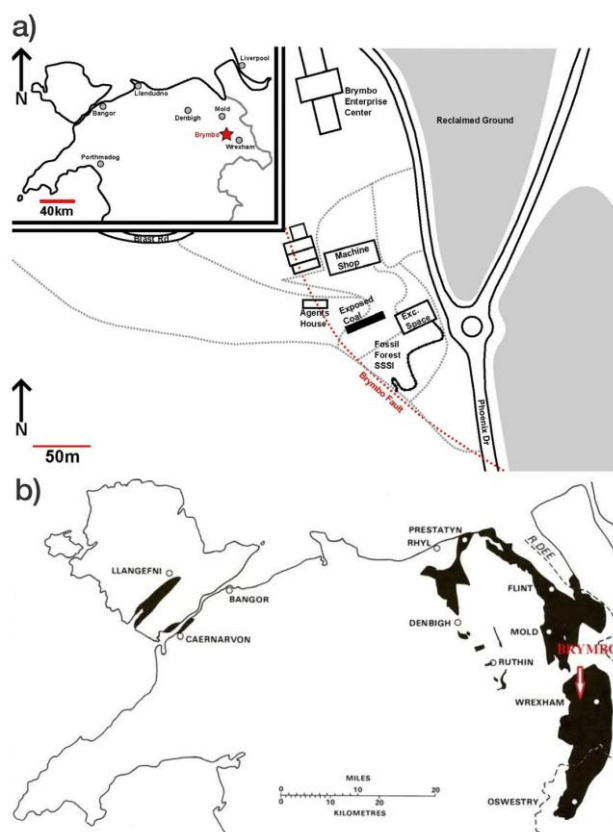


Figure 1. (a) Location of Brymbo Fossil Forest (BFF) with a red star and associated industrial buildings [8]. **(b)** Location of Brymbo Fossil Forest in the Denbighshire Coal Basin, North Wales (black colour), [2].

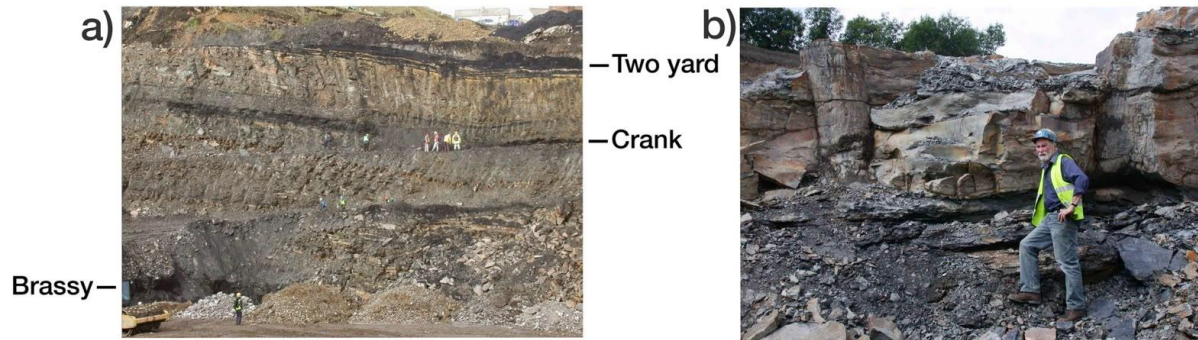


Figure 2. (a) Reclamation work at BFF site in 2005 showing several coal seams with clastic sediments in between (mudstones, sandstones, seat earths). This indicates the presence of cyclic deposition (cyclothems) in the area. Photograph by Peter Appleton. **(b)** Arborescent lycopod stump *in-situ*, an example of trans-stratigraphic fossil from the Brymbo Fossil Forest (BFF) sequence in 2005. Photograph by Peter Appleton



Figure 3. (a) Brymbo Fossil Forest building (BFF) in 2025, protecting part of the palaeontological site, which is part of the Stori Brymbo visitor geoheritage attraction. Photograph by Leon Bowen. **(b)** View inside the BFF building in 2026, notice the large amounts of *Calamites in situ* on top of the sandstone unit B6 and the on-site laboratory in green at the back.

Carboniferous Period

Eonothem/ Eon	Erathem/ Era	System/ Period	Subperiod	Series/ Epoch	Stage/ Age	millions of years ago
Phanerozoic ↑ ↓	Paleozoic ↑ ↓	Carboniferous	Pennsylvanian*	Upper	Gzhelian	298.9 ± 0.15
					Kasimovian	303.7 ± 0.1
				Middle	Moscovian	307 ± 0.1
					Bashkirian	315.2 ± 0.2
			Mississippian*	Upper	Serpukhovian	323.2 ± 0.4
						330.9 ± 0.2
				Middle	Visean	346.7 ± 0.4
				Lower	Tournaisian	358.9 ± 0.4

Figure 4. Stages of the Carboniferous, showing their ages and the position of the Moscovian.

After: International Commission on Stratigraphy (ICS), 2023.

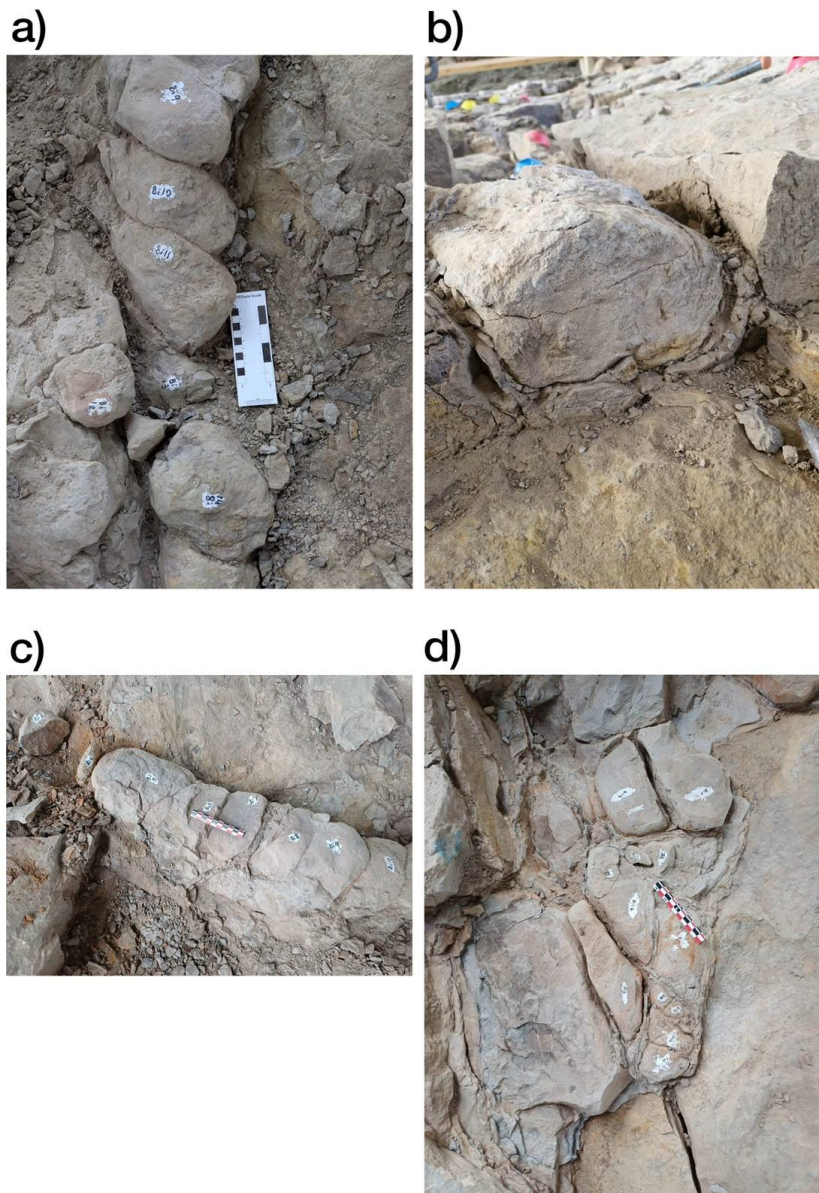


Figure 9. Examples of sandstone structures: “sausage roll” concretions present at the top sandstone unit, layer B6, surrounded by blue mudstones injected by soft sediment deformation. See also the QGIS maps in Figure 6 showing at least two main general directions of fractures at the site.

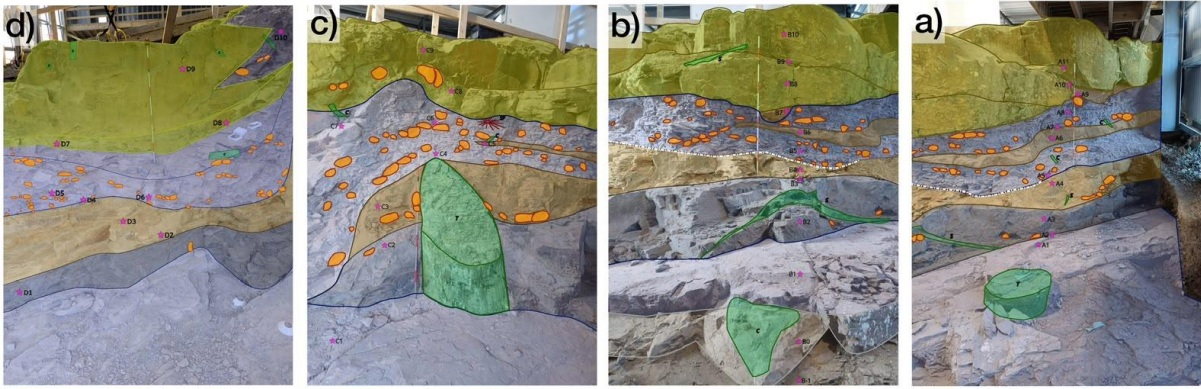


Figure 6. Stratigraphic sections studied at the site: **Sections 6a, 6b, 6c and 6d.** Notice the lateral variability in the thickness of the sediment units, associated with river channels.

Green: Fossil plants: co=*Cordiates*, c=*Calamites*, s=*Stigmaria*, T: Arborescent lycopod trunk. **Yellow:** Large medium sandstone infilled channels. **Light brown:** Small fine sandstone infilled channels. **Grey:** siltstone/mudstone layers. **Orange blobs:** siderite concretions. **Pink stars:** sediment samples. The location of the stratigraphic sections described is shown in the map of Figure 7a.

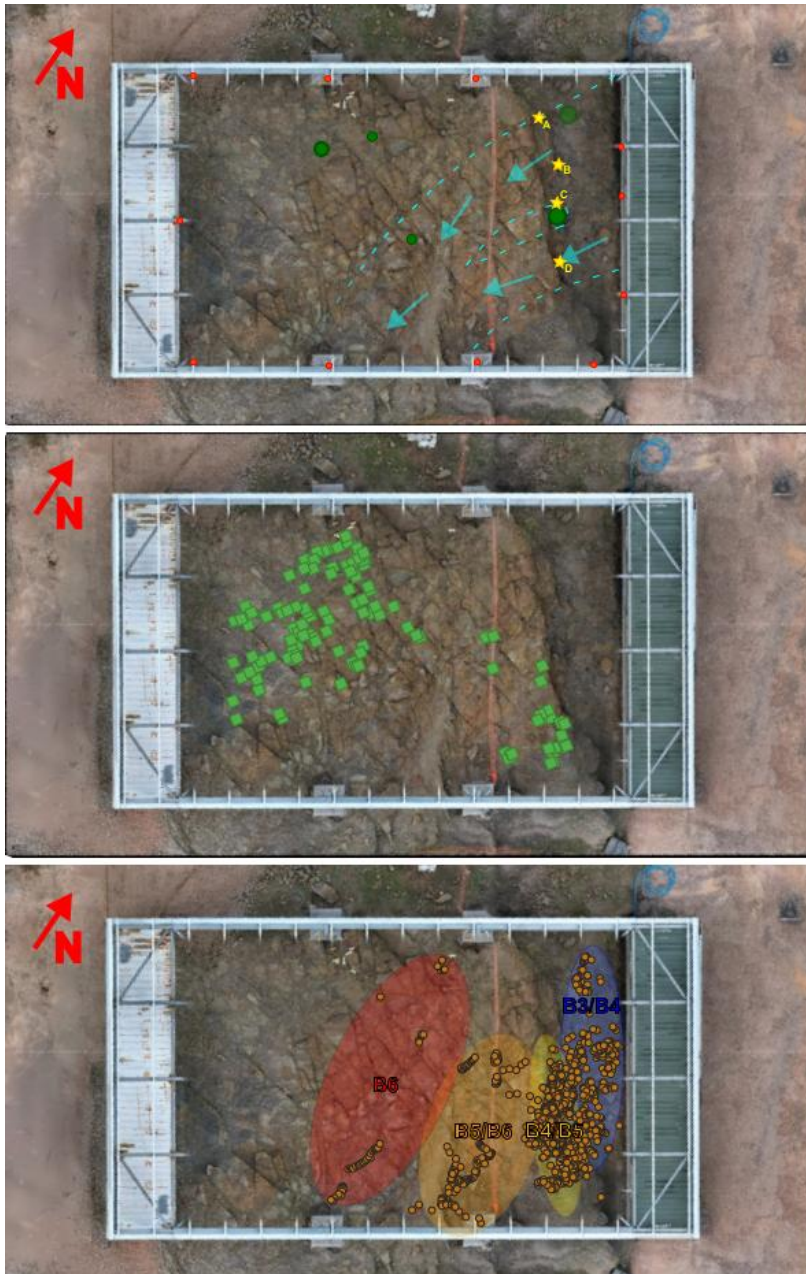


Figure 7. QGIS Maps of the Brymbo Fossil Forest (drone image of surface taken before completion of the FF building in 2025), data collected with a total station between 2025-2026. **(a) Top map** showing direction of interpreted channel flow in light blue. Red dots = Fixed points used for total station calibration. Green circles = in situ lycopod trunks. Yellow stars = location of stratigraphic sections described in Figure 6. **(b) Middle map** showing location of *in-situ* Calamatian horsetails found to-date (green diamonds). **(c) Lower map**

740 showing distribution of siderite concretions discovered so far. Coloured ellipses correspond

741 roughly to the strata indicated.

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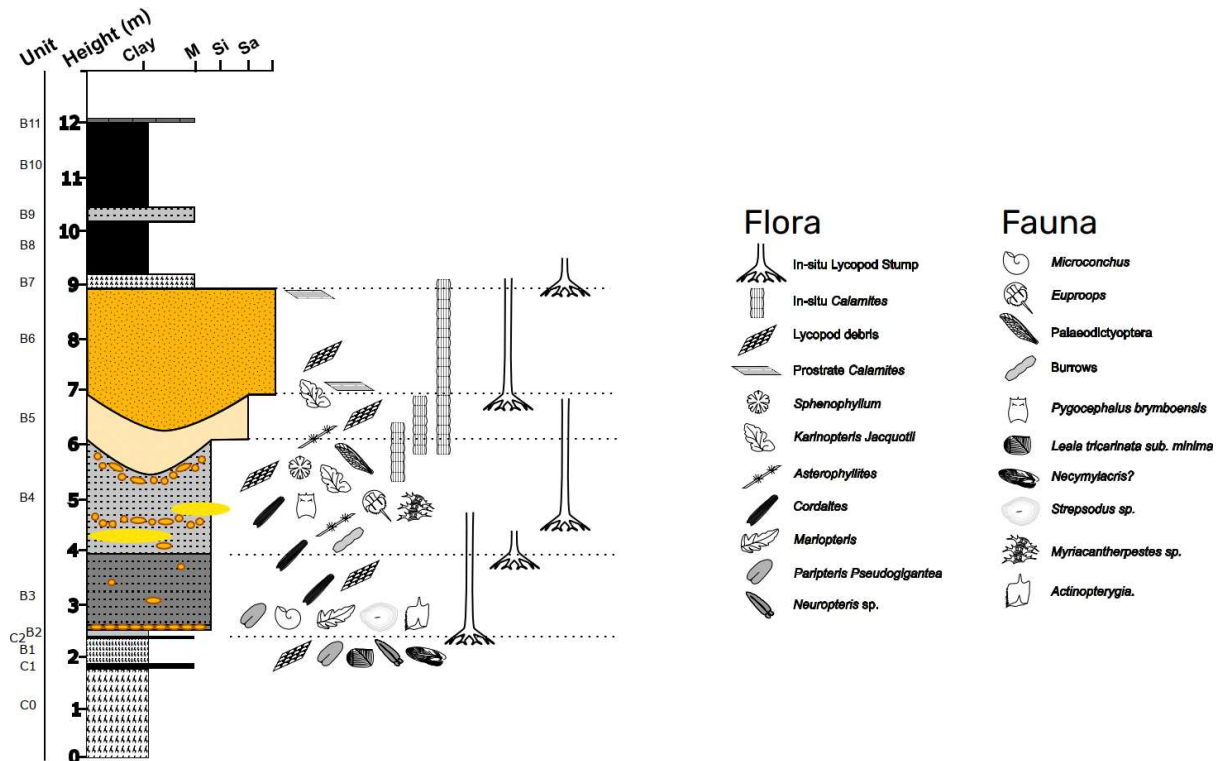


Figure 8. Brymbo Cyclothem general stratigraphic sequence with plant and fauna fossil associations. Fossils on dotted line indicate occurrence in contact of beds. Fossils crossing dotted lines implies trans-stratigraphic occurrence (*in-situ*): plants transgressing several sediment units) e.g. Arborescent lycopod trunks and *Calamites* stems *in-situ*. **Black colour:** coal seams. **Dark orange ovals:** siderite concretions. **Orange, cream and yellow:** sandstone channels of different sizes. **Abbreviations=** C: clay, M: mud, Si: silt, Sa: sandstone.



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752 **Figure 9.** Siltstone in layer B4, showing brittle deformation, around a *Stigmaria* root in its

753 centre, example of a “star fracture”. Scale in cm.

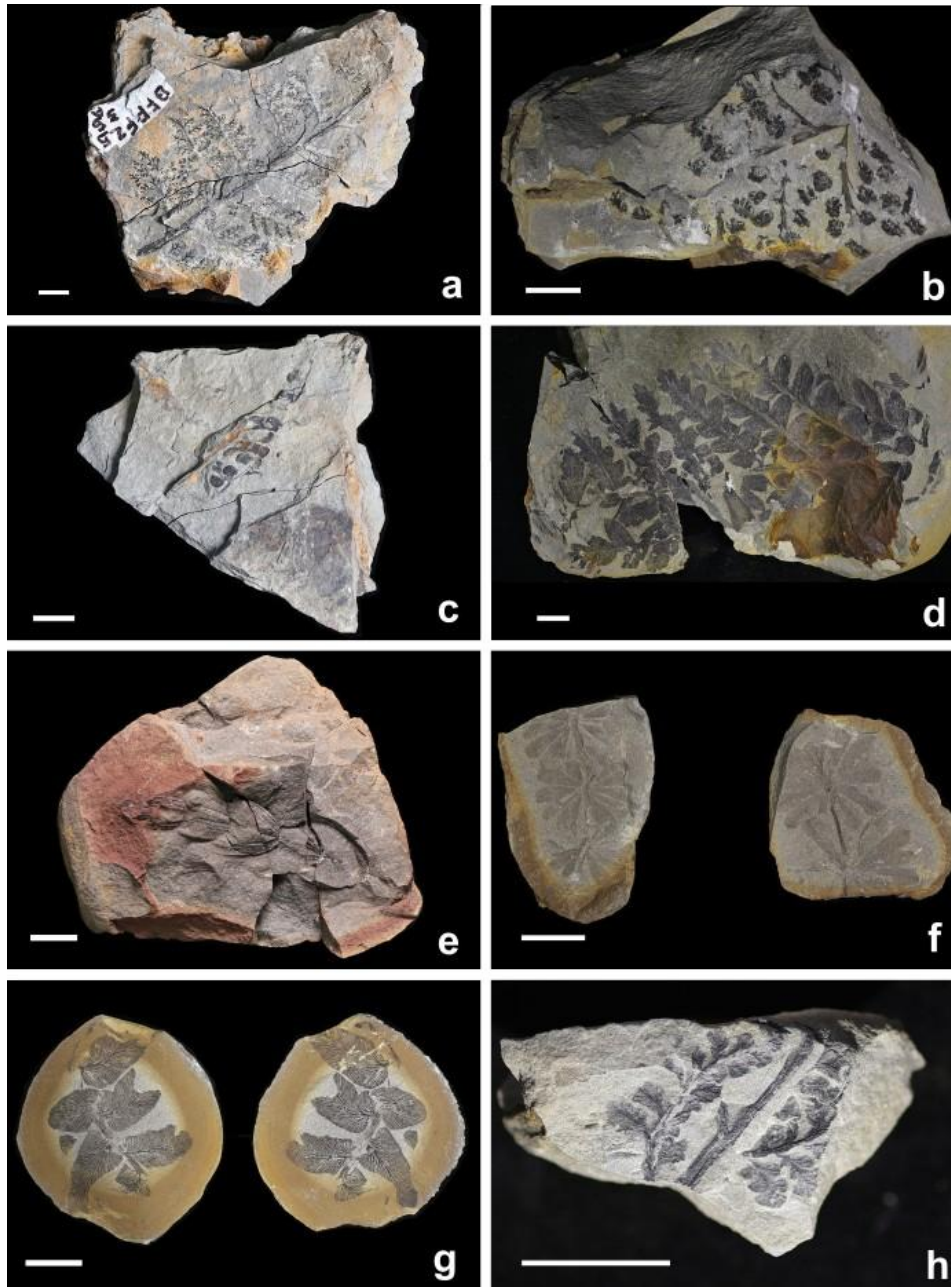


Figure 10a A selection of non-lycopod plant fossils found within the Brymbo Fossil Forest excavation during the period 2025 – 2026. **(a):** *Zeilleria fosteri* (BFFF2535a) frond preserved as a carbon adpression from the bottom of unit B4 **(b):** *Zeilleria fosteri* (BFFF26021.1) fructifications within a siderite nodule from the bottom of unit B4 **(c):** partial *Eusphenopteris* sp. (BFFC2570) frond from unit B4 **(d):** *Karinopteris jacquotii* (BFFC26093) within a large siderite concretion from the nodule band in unit B4 **(e):** *Asterophyllites equisetiformis* (BFFA25128a) within a siderite concretion from unit B4 **(f):** *Annularia* sp. (BFFA26125)

762 within a siderite concretion from unit B4 **(g)**: *Neuropteris* sp. within a siderite concretion
763 from unit B4 **(h)**: *Palmatopteris?* sp. (BFFC26023) adpression from unit B4. All scale bars =
764 1cm. Images by Frey Jones and Elisabeth Wilkinson.

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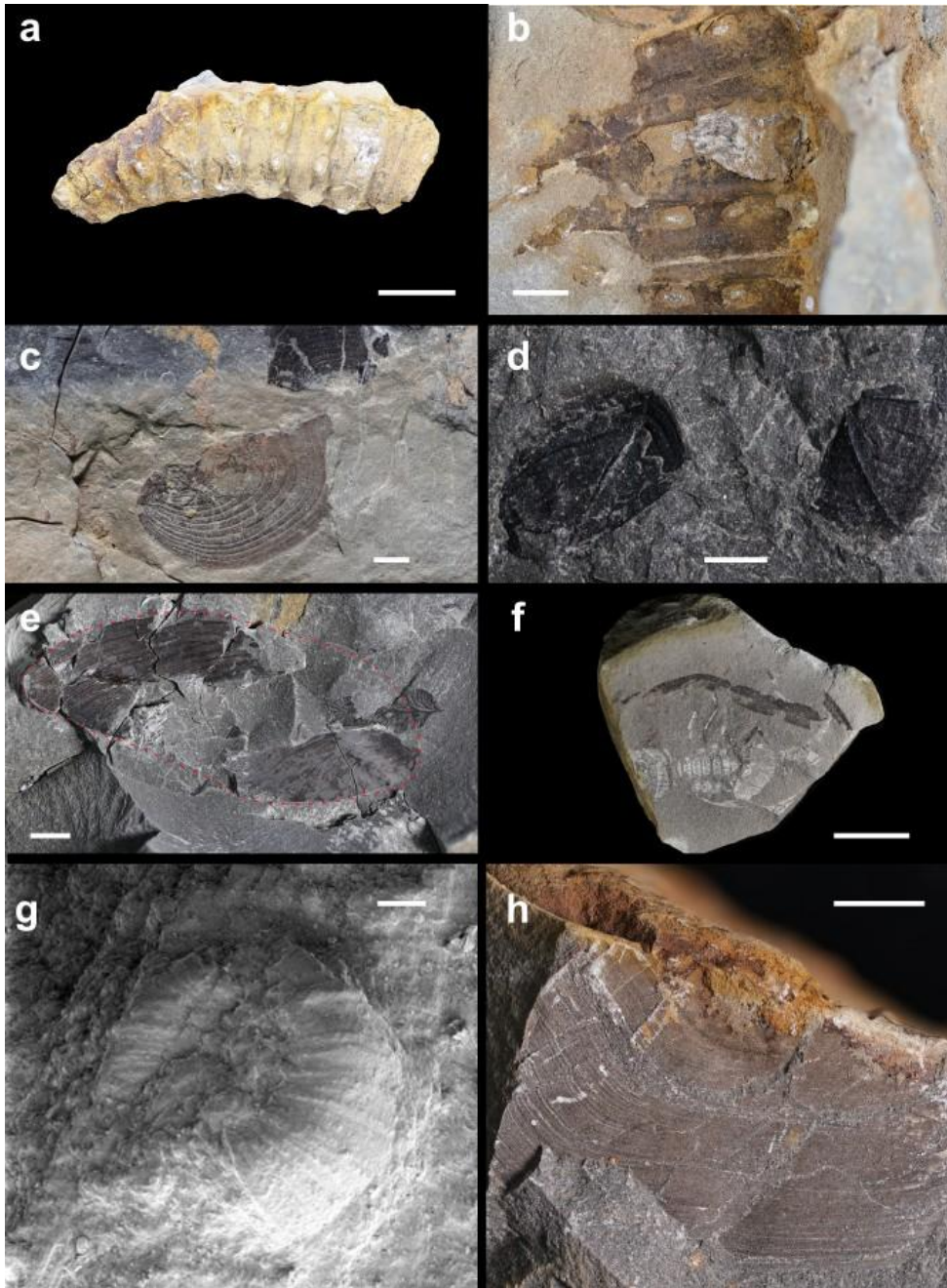


Figure 10b. A selection of the animal fossils found within the Brymbo Fossil Forest excavation during the period 2025-2026. **(a):** *Myriacanthepestes* sp. (BFFG26024) from a siderite concretion in unit B4 scale bar = 1 cm **(b):** counterpart to a, showing pleural spines scale bar = 1 cm. **(c):** unidentified spinicaudatan (BFFG26036) from unit B3 scale bar = 1mm. **(d):** *Leia tricarinata* sub. *Minima* (BFFG26033), a small spinicaudatan from unit B3 scale bar = 1mm. **(e):** Suspected partial Archimylacris (blattoidea) wing (BFFG26002) from unit B2/B3 scale bar = 1cm. **(f):** *Pygocephalus brymboensis* (BFFG26038) from a siderite

778 concretion in unit B4 scale bar = 1cm. **(g):** SEM of *Microconchus* sp. (BFFG26008) from
779 unit B2 scale bar = 100µm. **(h):** partial *Strepsodus* sp. (BFFL26001) scale from siderite
780 concretion in unit B3 scale bar = 1cm. Images by Frey Jones, Ewan Titcombe, Will Brighton
781 & Tim Astrop.
782

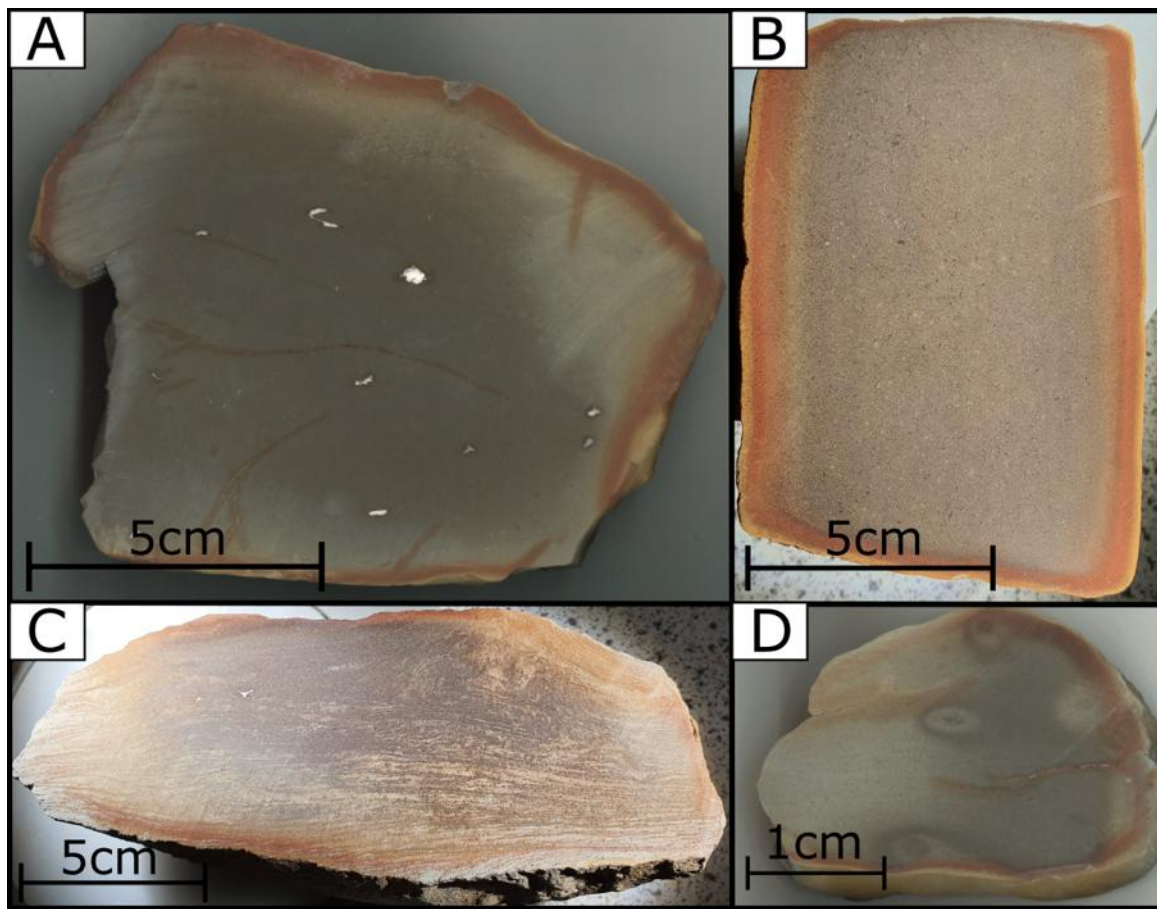


Figure 11. Selection of BFF siderite concretion samples, sawn in half. **(a)** Sample S3, entirely dark coloured, later found to contain highest % of Fe-rich siderite (Lighter areas are unpolished regions), white mineral was identified as kaolinite. **(b)** Sample S8, this concretion was replacing/infilling a calamites stem. **(c)** Sample S9, this concretion preserved laminations, lighter laminations were found to be quartz rich layers. **(d)** Sample S2, possible evidence for bioturbation can be seen in the round textures made up of different coloured siderite. Notice the orange oxidized rims in the outside of the nodules.

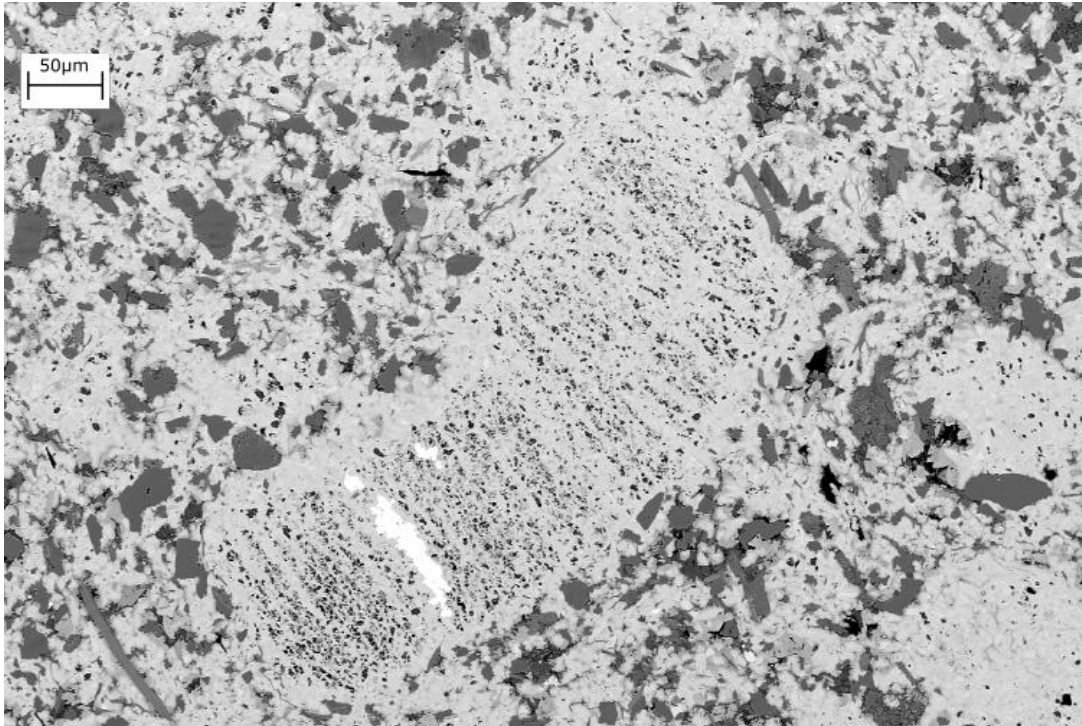
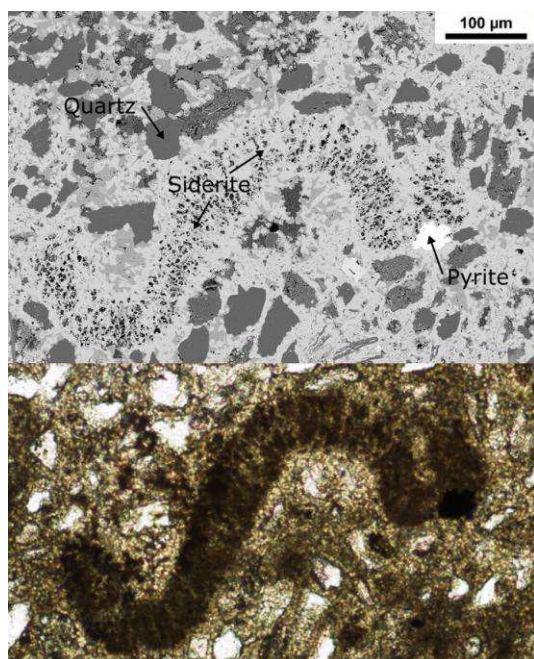


Figure 12. BSEM image from concretion S4, with a typical 'blotchy' texture as seen in most of the BFF concretion thin sections. Note the stratified nature some of the micropores and the occurrence of pyrite (bright white colour).



798

799 **Figure 13.** Concretion S9, under BSEM (Top) and transmitted light microscope (Bottom).

800 Notice the curled nature of this feature (biogenic?) and the more random orientation of
801 micropores.

802

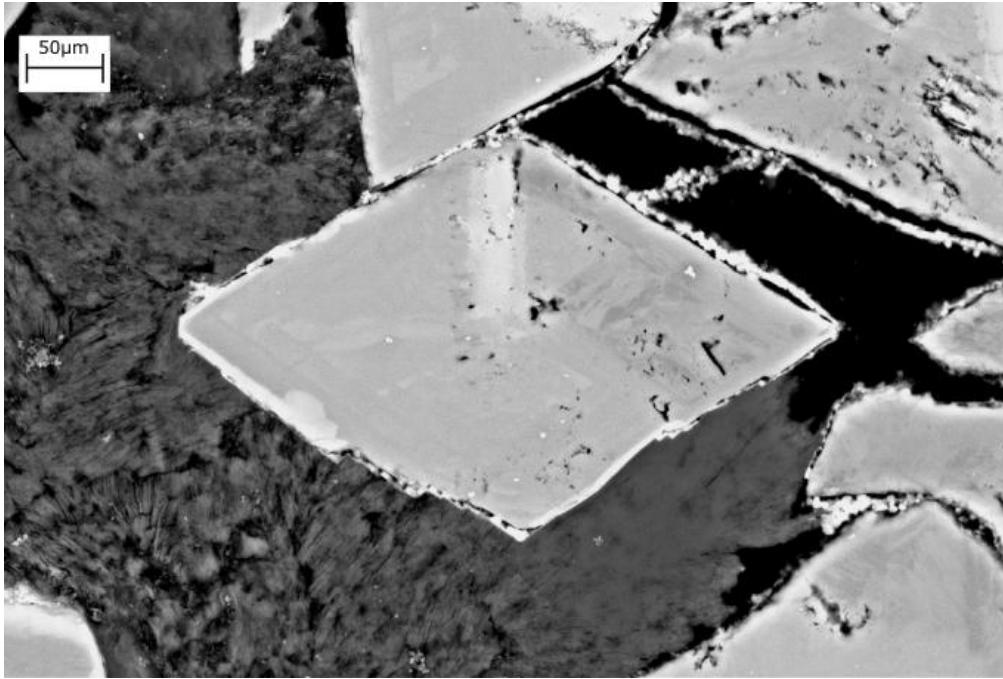


Figure 14. BSEM image of a single siderite crystal in concretion S13. The image has been adjusted to show the chemical zoning within the individual phases. This crystal is composed of nearly all Mg-rich siderite except for the lighter coloured strip in the centre. Also note the outer edge reaction rim showing evidence of dissolution as well as the micropores on part of the grain boundary between Fe-rich siderite and Mg-rich siderite.

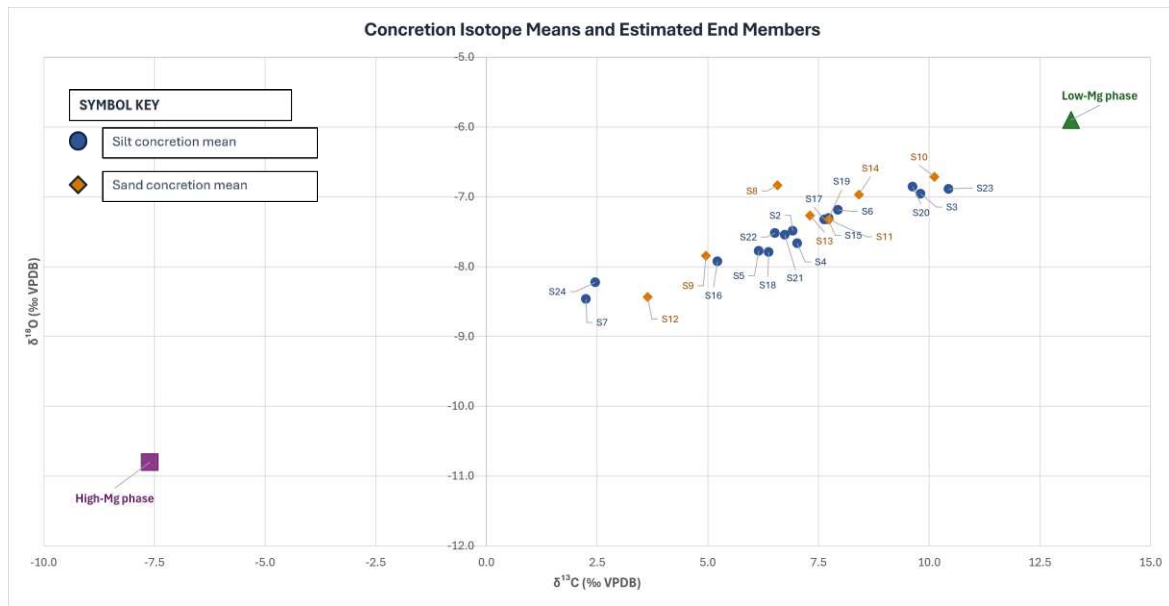


Figure 15. Covariance isotope plot showing mean values for each concretion (labelled) along with the estimated values for the end member siderite phases. Blue circles are concretions hosted in siltstone; orange diamonds are concretions hosted in sandstone. Note how the original mixing trend obscures the true values of the phases and therefore any environmental interpretations from them (for methodology, see [7]).

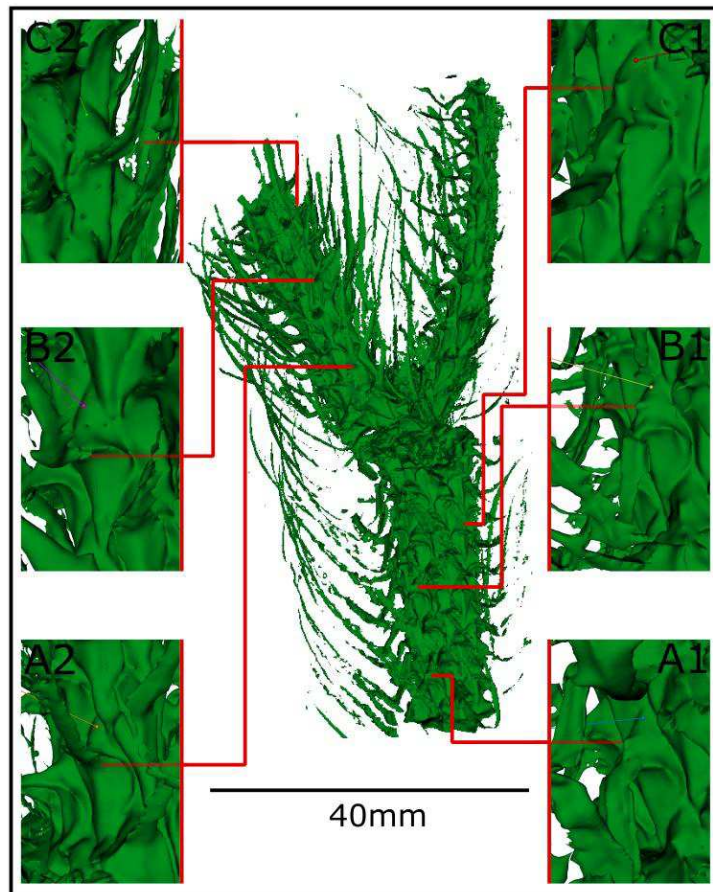


Figure 16. The three-dimensional reconstruction of the *Lepidodendron* branch specimen, using μ -CT data. A1, B1, C1, magnified images of leaf cushions found pre-bifurcation with a currently unidentified protrusion located above the leaf lamina attachment point. A2, B2, C2, magnified images of leaf cushions found post-bifurcation without the currently unidentified protrusion. **Scales bar = 40mm.**



824

825 **Figure 17a.** Reconstruction of the palaeoenvironment at the BFF during the deposition of the
 826 mudstone/siltstone units (B3 and B4, Figure 8). These units are associated with flooding of
 827 water into a lagoon/crevasse splay, where the fine lamination preserves broken down plant
 828 debris, with multiple episodes of gradual sediment input. The fragmented plant debris is often
 829 preserved as adpressions, including climbing ferns, tree ferns, *calamites* and lycopod leafy
 830 branches and cones. Reconstructions of two of the fauna: *Pygocephalus brymboensis* and
 831 *Euproops sp.* are presented in the insets below (Illustration by Tyler Carter).

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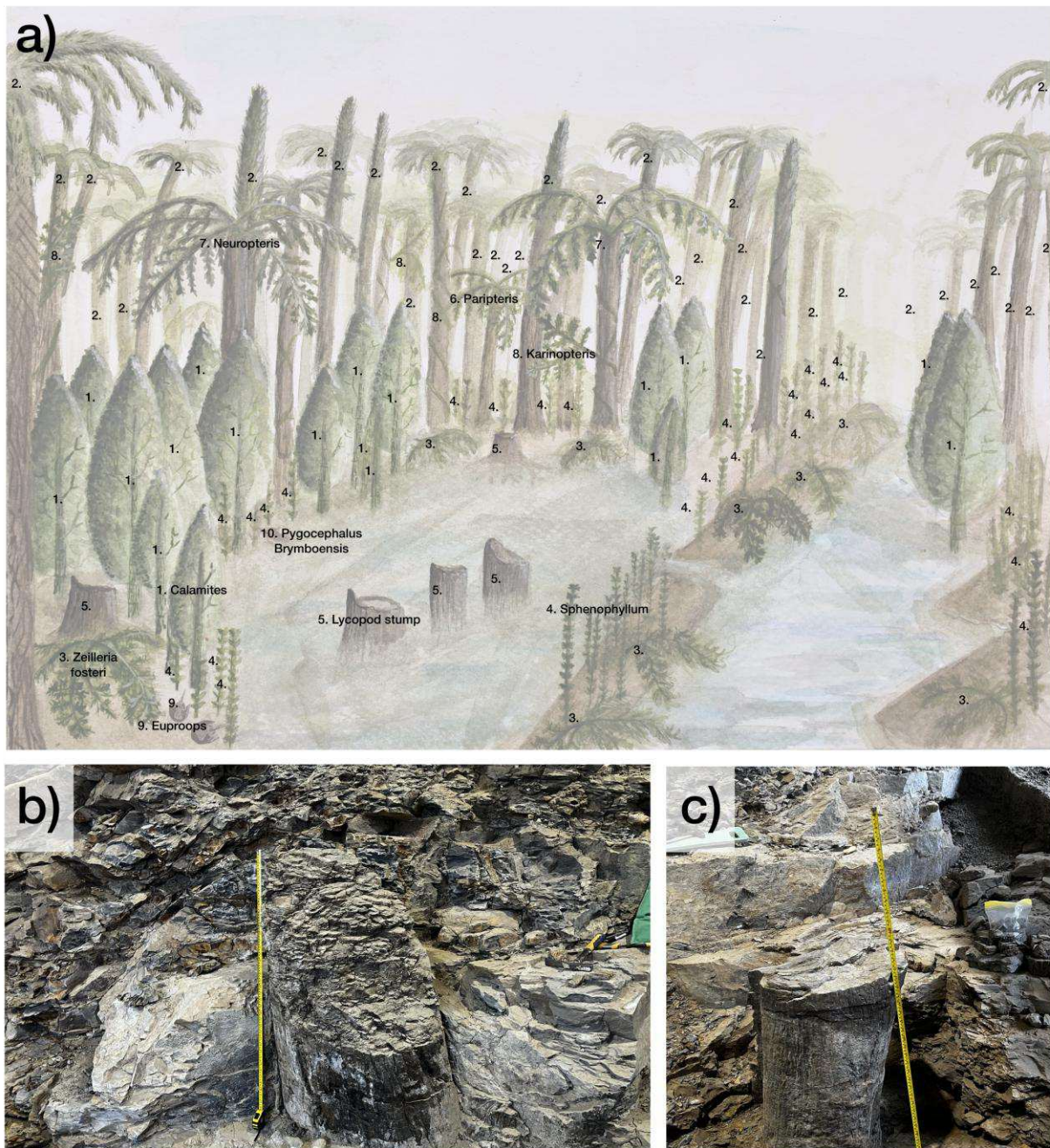


Figure 17b. Labelled reconstruction of the palaeoenvironment during the deposition of the mudstone/siltstone units (B3 and B4). Flora and fauna found preserved within these layers are labelled with their identities. **(b)** Large lycopod stump (trans-stratigraphic fossil), with partial burial though the lower mudstones. **(c)** Large lycopod stump, partially buried through the lower mudstones.



840

841 **Figure 18a.** Reconstruction of the palaeoenvironment during the deposition of the sandstone
 842 units (B5 and B6 from Figure 8), associated with meandering river channels which have
 843 scoured bases. This is associated with fast, rapid flooding. Many *in-situ Calamites* have been
 844 excavated from these units along with many prostrate *calamites*, deposited aligned with the
 845 flow direction of the channel. The *calamites* pith casts dominate the fossils found in this unit,
 846 along with some tree and climbing fern remains and a few large lycopod stumps. No fauna
 847 has been found preserved within this stratigraphy (Illustration by Tyler Carter)



848

849 **Figure 18b. (a)** Labeled reconstruction with the flora found in B5 and B6. **(b)** Prostrate log,850 across a sandstone channel, a high density of climbing ferns, primarily *Karinopteris jacquotii*

851 have been found preserved as carbon films around the log. This indicates a log jam

852 represented in the reconstruction above. **(c)** Prostrated large calamites trunks, aligned with the

853 direction of flow of the channel. (Scale bar, a and b = 100cm).

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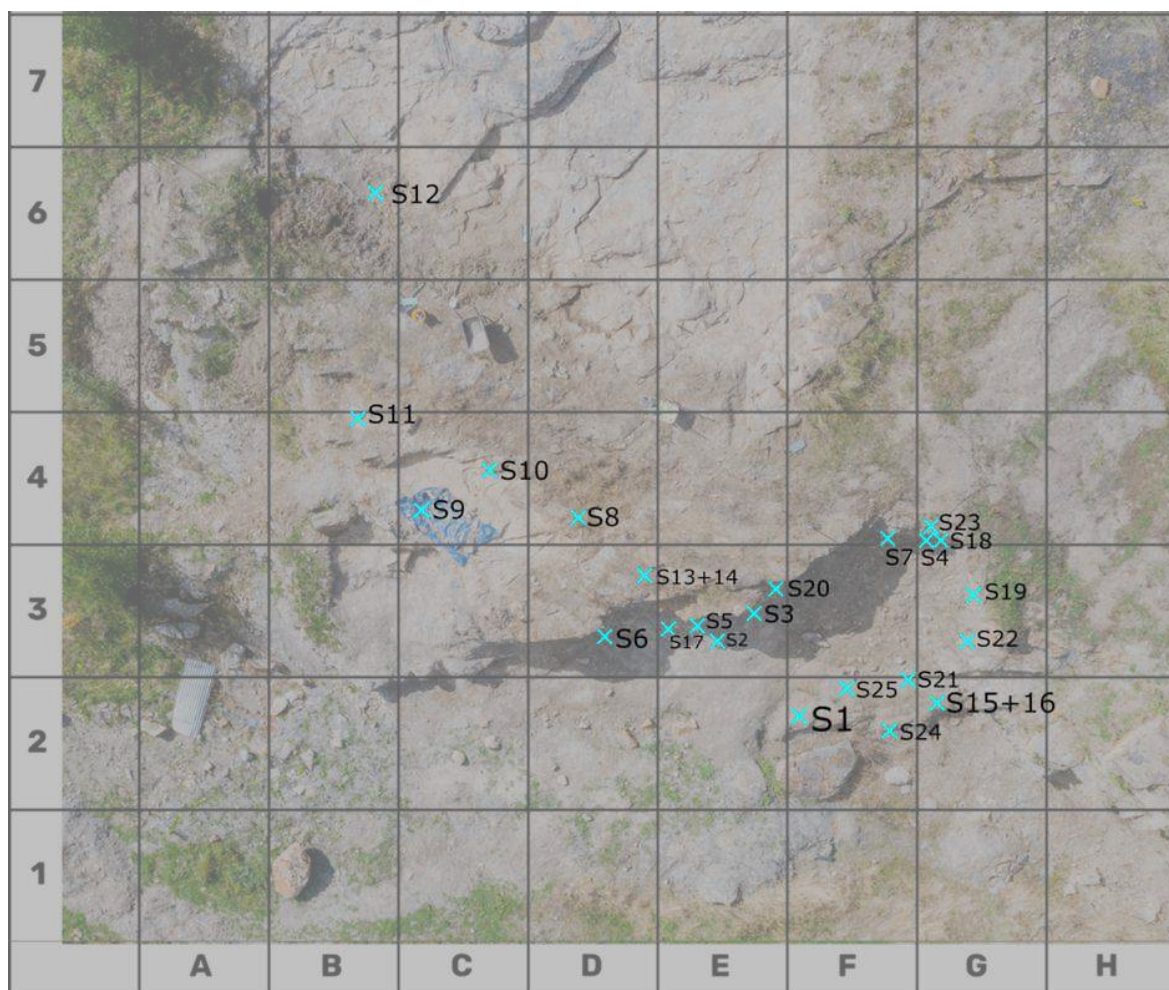


Figure 19. View from above of the main BFF outcrop in 2023, showing locations of the siderite concretions samples taken for this study. Image taken before the BFF building was constructed on top [7].

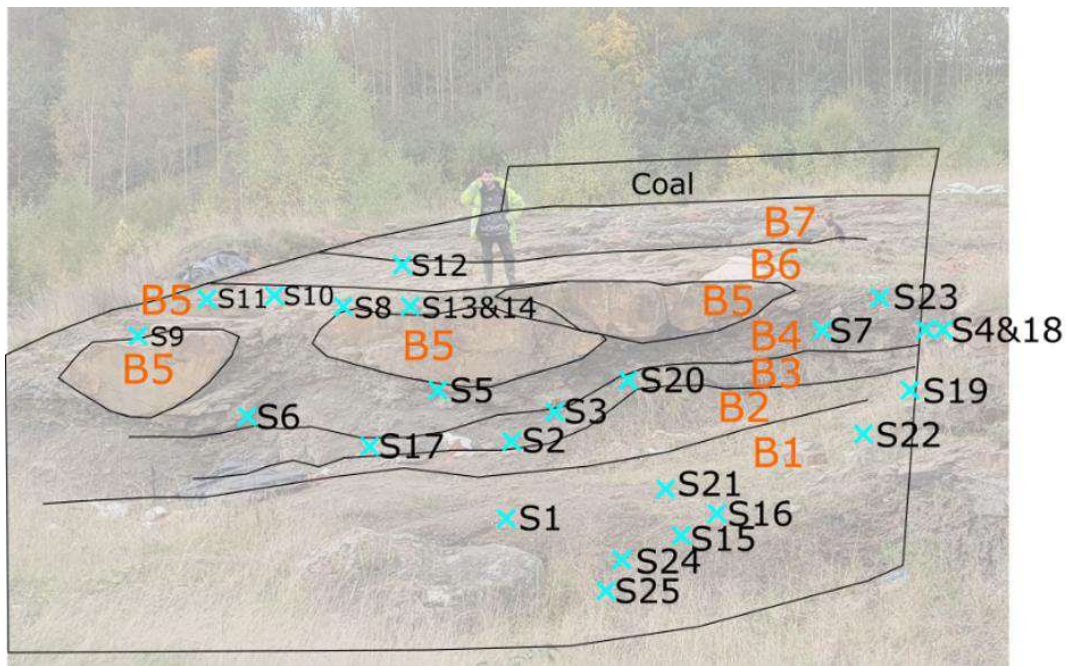


Figure 20. View of the outcrop section at BFF in 2023, showing a sketch of the logged bedding and siderite sample locations with blue crosses. Note the multiple distinct river channels making up beds B5 and B6. Nomenclature for the sediment layers taken from Hughes [7].

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882 Writing-original draft: S.G. led the writing with contributions of all coauthors. Writing-
883 review and editing: S.G., T.A.

884 **Competing Interests**

885 There are no competing interests.