The origin of the Carboniferous coal measures—part 1: Lessons from history

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Early geological researchers into the coal measures of the Carboniferous System sought to explain its origin in terms of geological processes operating over eons of time. Yet the evidence that they were continually uncovering presented more and more difficulties within that framework of thinking. Particularly troublesome were the difficulties relating to the roots of the fern trees, the dominant Carboniferous vegetation. The confusion even extended across national borders with the ideas of the geologists on the Continent conflicting with those in England and America, such as the Silvomarine hypothesis of the German Otto Kuntze. This confusion led the early geologists to devise secondary hypotheses to salvage their paradigm, hypotheses that are today part of the standard explanation for the origin of coal but are still inadequate to resolve the problems. The evidence suggests that geological processes were qualitatively different and of a larger scale than the pioneers of the discipline were prepared to consider. In other words, their paradigm needs updating.

Focusing on the Carboniferous

The Carboniferous was the very first complete section of the geological column to have been described. The name 'Carboniferous' or 'coal-bearing' (from 'carbo', the Latin for 'coal', plus 'fero', the Latin for 'I have') was proposed by the English geologists William Conybeare and William Phillips in a paper published in 1822 to designate the coal-bearing strata in north-central England. Conybeare and Phillips' Carboniferous Order included the Mountain or Carboniferous Limestone at its base, the Millstone Grit (or graywacke) in the middle, and the Coal Measures on top.[1]

As the early geological researchers sought to explain the origin of the coal measures and to understand the fossils contained within the measures, they thought in terms of modern depositional environments. Their framework of thinking involved geological processes that operated slowly over eons of time, yet they uncovered evidence that demanded processes of larger scale than they were prepared to consider. As they encountered more and more anomalies that contradicted their expectations they resorted to secondary hypotheses that are still part of the standard explanation today, but which are still inadequate to account for the evidence. A review of the historical development of geological explanations for the origin of the Carboniferous Coal measures will be given because this will help us understand the issues involved as well as the problems that remain unresolved to this day.

The challenge to explain the fossils

Despite there being an incredible biodensity indicated by the abundance of fossils in the Coal Measures, there was a disturbing lack of biodiversity in them. They presented numerous well-preserved examples of fragments of plants, but they emphatically did not contain easily-found samples of the whole of these organisms. So prevalent was this disarticulation and so unfamiliar were some of the flora in them that the early pioneers were forced to place the fragments into 'form genera' instead of being able to describe genera of whole plants (figure 1).[2] They did this in order to make any progress at all. That is, those interested in the subject produced descriptions and graphics of *parts* of the plants, waiting for future fossil evidence to illuminate the relationships among them.

One illustrative case of the challenges they faced was that of classifying the bark or periderm of the predominant fern trees (the lycopods) of the Upper Carboniferous. These often occurred in flattened and fragmented sections. Different layers of lycopod bark with different patterns soon became different form genera. In fact, lycopod bark from the same layer of the tree but situated at different levels on it also gave rise to different form genera.

This was typical for all the parts of lycopods. Hence a single lycopod fern-tree could have rootlets, roots, different layers of bark, various protuberances in the bark, leaves, seeds (i.e. integumented megasporangiums), and spores all in different form genera (figure 2). This was also true for other Carboniferous plants. Indeed, there were even cases of the same part of a Carboniferous plant being placed in different form genera due to its having undergone more than one type of distinct fossilization.

Despite there being an abundance of lycopod fern-tree trunk fossils (as examples, *Sigillaria* and *Lepidodendron*), they were found to be disturbingly separated from any roots (the *Stigmaria*), were often casts (implying a hollow or easily-destroyed interior), and were sometimes found as flattened or decorticated bark. Concerning fragments of *Stigmaria* (the roots—figure 3) without *Sigillaria* (the trunks), C.W. Williamson, the leading expert on *Stigmaria*, stated "How these roots have so often become disturbed and broken up is a question not easily answered."[3]

Not surprisingly, the separation of the *Stigmaria* from the fern-tree trunks initially caused a great deal of consternation. The problem was that such excellent preservation combined with disarticulation of the trees pointed to catastrophe rather than slow deposition over millennia by present processes

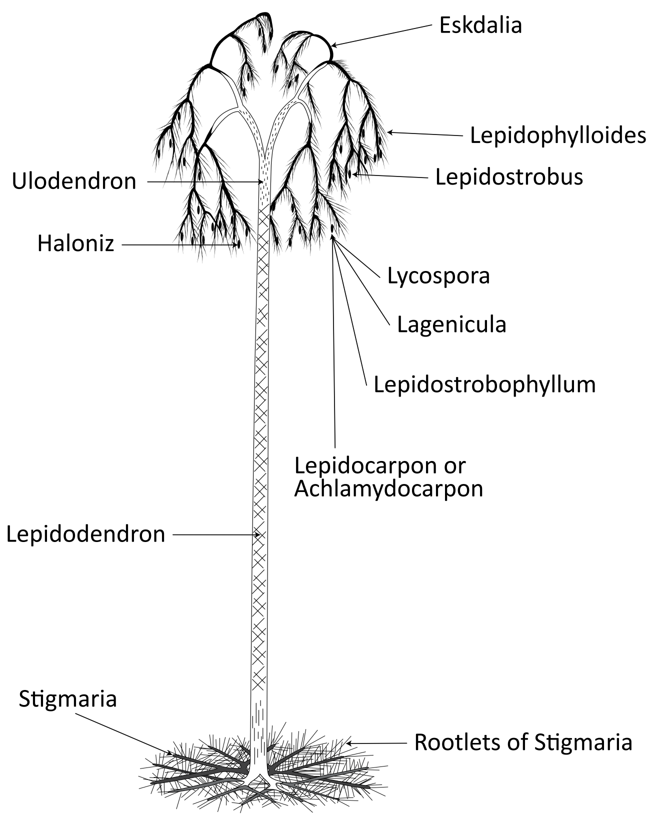

Figure 1. Schematic of a Lepidodendron fern tree showing the location of some of the numerous 'form genera' associated with it.

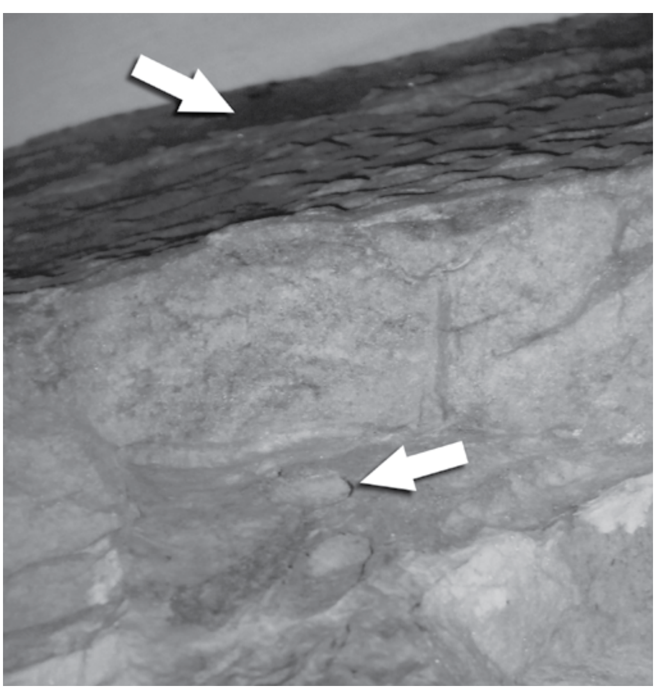

Figure 2. An interpretative challenge: flattened lycopod bark (arrow at top) in close proximity to a Stigmaria (its central core or stele is the cylinder at the bottom center—bottom arrow). This is a typical occurrence in the sandstone layer immediately below the Middle Kittanning Coal of Portersville, Pennsylvania, United States of America. (Collection of Daniel A. Woolley)

within a swamp, as they had expected from their geological philosophy. Some extent of the intensity of the catastrophe involved can be gleaned when we examine quantitatively the forces necessary to shear the trunks and limbs of these trees.[4]

Especially disconcerting was the fact that the *Stigmaria* (the roots) were found in different stratigraphic layers than the trunks. At first it was thought that the *Stigmaria* were a sort of succulent aquatic plant with its rootlets being considered its leaves.[5] Yet these leaves were arranged spirally around the main root (like a little brush). The mystery was eventually solved when Binney found a *Sigillaria* (the trunk) attached to *Stigmaria.* Then, to produce an amazing confusion out of this newly-found order, in the Cape Benton Coalfield a *Stigmaria* was found attached to a *Lepidodendron* (the other type of dominant Lycopod trunk)! So there was the unprecedented situation of having one uniquely distinguishable root fossil for two readily differentiable and dissimilar tree-sized plants. This quandary has gotten worse due to additional fossil finds.[6]

One late nineteenth century researcher summarized the state of wondrous confusion as follows:

> "All the geologists who have examined the distribution of the carboniferous measures and the composition of the strata have remarked the predominance of *Stigmaria* in the clay deposits which constitute the bottom of the coal beds. As the remains of *Stigmaria* are always [*sic*] found in that peculiar kind of clay and also in the intervening siliceous beds generally called clay partings, without any fragments of *Sigillaria*, it has been supposed that the clay materials were merely a kind of soft mould where the *Sigillaria* began their life by the germination of seeds and there expanded their roots, while their trunks growing up did contribute by their woody matter the essential composition formed above clay beds. This opinion has the appearance of truth indeed. But how to explain the fact that beds of fireclay twenty to thirty feet [6 to 9 meters] in thickness are mostly composed of *Stigmaria*, or filled from the base to the top with remains of these plants, stems, and leaves, without a fragment of *Sigillaria* ever found amongst them and without any coal above? Roots cannot live independently of trunks or of aerial plants."[7]

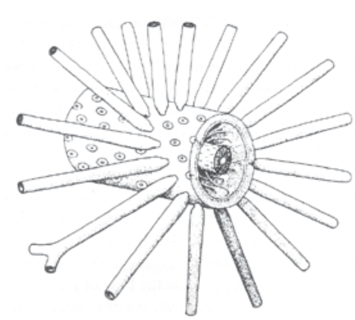

Figure 3. Schematic of *Stigmaria* structure, including radiating rootlets.

The abundance of ferns in the coal and shale layers led to the conjecture that the environment in which they flourished was a warm or tropical one. Of course, as noted very early by Charles Darwin (in his well-known *Voyage of the Beagle*), peat-forming swamps do not exist in the tropics: they are confined to the temperate zones.[8] Not only that, but once the extent of Carboniferous coals became known, their phenomenal distribution in area and uniformity in thickness and flora composition became problems of the greatest magnitude. This did not go unnoticed in the non-English-speaking world.

Furthermore there was an unstated but rather natural assumption that the fern foliage that was so similar in appearance to that of modern ferns reflected a plant that was closely related to them, occupying the same ecological niche. It wasn't until the beginning of the twentieth century that two researchers were able to discern by clever deductions from fossil evidence that these ferns were seed ferns whose seeds may have been well suited to an aquatic environment.[9] By that time paradigm paralysis had set in, and the premature hypotheses became standard working assumptions.

Problems with the notion of Paleozoic swamp-generated coal

The inferences of the early English and American researchers concerning the coal measures tended to differ from those of some German and French scientists. The English-speaking geologist milieu quickly ran into a multitude of seemingly inexplicable observations, ones that pointed to the untenable or questionable nature of their favored premature explanation of coal having formed in ancient swamps. Some of these observations and the complex explanations of the English-speaking geologists will be dealt with first and then the contrasting work of Continental geologists will be examined.

A rather direct challenge to the idea of the swamp genesis of coal was the existence of marine fossil tube worms (figure 4), among other marine fossils, attached to the exterior, and sometimes the interior, layers of *Sigillaria*. These were seemingly identical to contemporary descendants of these animals. Dawson argued that these *Spirorbis carbonarius* fossils came from "closed lagoons and estuaries" because they could be found on the inside of *Sigillaria*, supposedly indicating that these Lycopods were dead and hollow when the infestation occurred.[10]

Charles Lyell saw the same evidence as indicating marine invasion of ancient coastal swamps, even coming up with an inadequately small-scale contemporary analogue from an extremity of the Mississippi Delta to buttress his argument.[11] The incongruity of this explanation is obvious: continent-sized coal layers were supposedly invaded pervasively by coastal phenomena! These *ad hoc* arguments or fixes to the problem of maintaining the swamp explanation for the coal measures in the face of conflicting evidence certainly seemed to fail in the matter of scale, if not in other aspects.

The sandstone wedges in the coal measures were another problem. These were expected to be aligned in one direction given the unbelievable uniformity of the coal layers and the expectation of sediment transport analogous to that observed today. However, they were not. Instead the wedge-shaped strata varied in almost every layer. It was as if they had been deposited by numerous rivers flowing from every direction into a closed sea or large lake. Furthermore, all the rivers had unnaturally wide mouths.[12]

To overcome this problem, geologists suggested that widely-spread simultaneous changes in land levels were responsible for both the wedge patterns and the uniformity and purity of the coal layers.[13] Edward Martin commented on this: "[T]he astonishing part of it is that the changes in the level of the land must have been taking place simultaneously over these large areas." He also quipped that "[F]orms of 'flora' found in the coal-beds in each country bear so close a resemblance to one another" that the suspicion was aroused that they unnaturally ignored latitude.

Furthermore, considering the thin clay and shale partings in the coal, it was observed that it was surprising that so little sediment found its way into the coal itself. But this was ingeniously explained away by Charles Lyell when he noted that Cypress swamps at the mouth of the

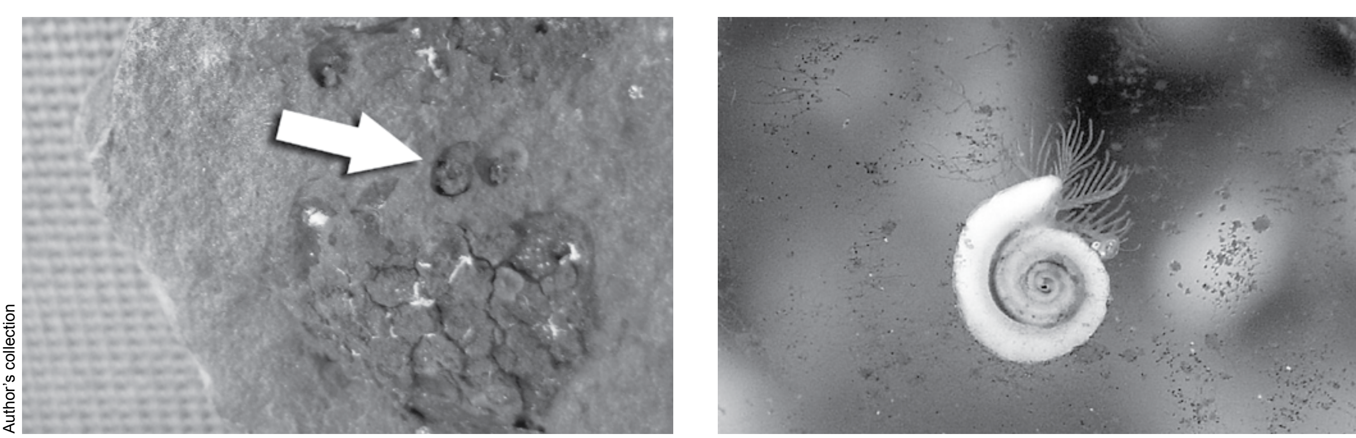

Figure 4. *Spirorbis* (marine tube worm) fossils (left) from supposedly swamp deposits from Mazon Creek, Illinois, United States of America. Living *Spirorbis* (right).

Mississippi River filter out the sediment, leaving periodic floods to account for the coal 'partings' of sandstone or shale.[14] As it was stated at the end of the 19th century by one geologist, concerning the artifice of using large-scale uniform changes in the elevation of the land to explain the multiple layers of coal: "Many a hard geological nut has only been overcome by the application of the principle of changes of level in the surface of the earth, and in this we shall find a sure explanation of the phenomena of the coal-measures."[15] The idea of doing a geodynamical calculation to test the feasibility of such speculations seemed to be anathema to this new breed of geologist.

Figure 5. Otto Kuntze's reconstruction of an Upper Carboniferous floating forest appeared in both his books on the subject (Otto Kuntze, ref. 19, frontpiece and *Geogenetische Beitrage*, Gressner and Schramm, Leipzig, p. 72, 1895.)

Still, there were more troubling anomalies that plagued those promoting a swamp origin for the coal measures coal. Coal layers often times were discriminating in what plants they contained. In the Joggins, Nova Scotia area, at least two of the 56 coals were found to be composed almost entirely of leaves.[16] Unnatural plant associations were found, such as roots fossilized next to bark, and ferns or Stigmarian rootlets invading calamite stems. The relative absence of fauna in the Carboniferous was accompanied by the presence of 'land reptiles and land snails' *within* the hollow fern-tree trunks there.[17] The biodensity of the apparent coal environment was phenomenal, yet the biodiversity was remarkably low.

In addition, coal layers were seen to bifurcate or split cleanly, without a hint of a facies-like transition.[18] There were hundreds of coal layers stacked one upon another in the associated repetitive strata units. And always there was the problem of scale, of their immense geographical extent. In an exacting science like physics, the immense scale of the deposit alone would have been termed a 'catastrophe', but all these anomalies drew scant attention as hard geological questions were answered by clever arguments, however tortuous those arguments may have been.

The Silvomarine hypothesis

The English and American geologists may have reached a metastable consensus regarding their speculations on the swamp origin of coal but that did not prevent a Continental scientist from coming up with an alternative explanation that addressed the difficulties without reliance upon a plethora of contortedly clever arguments. Otto Kuntze was a German botanist whose first love was geology. In his pioneering 1884 book entitled *Phytogeogenesis: Die Vorweltliche Entwickelung der Erdkruste und der Pflanzen in Grundzugen* (Phytogeogenesis: A basic outline of the prehistoric development of the earth's crust and plants), later supplemented by his book *Geogenetische Beitrage* and subsequent publications, Dr Kuntze came up with many disturbing and cogent arguments challenging the peat-forming swamp paradigm for the formation of Upper Carboniferous coal.[19] He pointed out further salt water species that were to be found in these coal layers, as well as many fresh water and terrestrial ones.

He sampled and chemically analyzed an incredible geographic distribution of coals and consistently confirmed that the coal measures were always associated with a marine environment when they were Upper Carboniferous (and a continental one when they were Tertiary).[20] He confirmed and reported upon what others had observed about the odd distribution of upright but truncated and hollow lycopod logs being stratigraphically separated from their roots. He noted a full-scale experiment that showed the upright placement of logs was likely to be the case for some time after their denudation and aqueous deposition; although he admitted to being baffled by the separation of lycopod trunks from their roots.

He speculated that a coal-forming swimming mass or mat of leaves, bark, etc. was likely to be hydrodynamically separated from the trunks and roots of the lycopod fern trees. He had trouble explaining the mechanism for the burial of the repetitive Pennsylvanian coal layers, especially the intervening limestone layers associated with them, but he finally settled upon a windblown or aeolian origin for these observed sediments. Falling victim to the uniformitarian framework of thinking, which requires a full explanation in terms of present processes, his aeolian-origin hypothesis was a weak link in his otherwise strong case. It tended to present problems of scale—problems of scale, ironically, being one of his primary arguments against delta splay formation of coals.

Kuntze also proposed that the Upper Carboniferous coals were formed from floating forests (figure 5), the likes of which do not exist today (even though he was able to find small-scale floating island analogues in the Rio Paraguay and Mississippi rivers). These forests had as their matrix or core a mass of lycopod fern tree roots that were interlocking with stiff rootlets that he suggested were used to fend off animal predators. They were in a non-acidic marine environment, floating on or just below the surface, depending on the maturity of the lycopod trunk (which would sink with age as he noted in some present-day partial analogues from Scandinavia and Switzerland). Surprisingly, he believed the upward-pointing rootlets on the lycopod stigmarian root were exposed to the air (while believing the downward ones were immersed in a muck).

The coal-forming floating forests, which Kuntze dubbed "silvomarine", had to have been washed into place, according to him. His arguments were based on the disturbances of the flora forming the base of them as well as their apparently having been laid down on limestones (including a Devonian one in Russia), shales, granites, gneisses, slates, and other silicate stones. Finally, according to Kuntze, the flora and fauna extinctions of this period were due to total habitat destruction of the silvomarine environment.

Kuntze is to be credited with not having followed the English lawyer Lyell's propensity to apply local or coastal observations to continent-sized coal deposits. However, like Lyell and the English-language geologists, he steered clear of mechanical or physical calculations (despite having applied quantitative chemical analyses in his reasoning). Statistical arguments were absent from his whole argument.

Generally speaking, any consensus about the origin of coal tended to be confined within narrow, almost national boundaries. The English and American scientific communities held *in situ* (autochthonous) interpretations of the origin of coal while the French and some German scientists held the floated-in view (allochthonous). It would be a long time before experimental evidence would be found to clarify this question.[21]

Conclusion

Early geological researchers sought to explain the origin of the coal measures in terms of modern depositional environments that involved geological processes that operated over eons of time (conforming to an historical and cultural deist milieu, which seems to have been a major driving force). Yet the evidence that was uncovered from the Carboniferous coal measures presented more and more difficulties within their framework of thinking.

Problems that presented themselves included the incredible biodensity of fossils in the coal measures coupled with a lack of biodiversity; the disarticulation of the fossils coupled with their excellent preservation; the separation of different parts of the same object, such as roots and trunks, into different stratigraphic layers. Other anomalies included the presence of marine fossils in supposedly terrestrial deposits, the immense lateral geographical extent of the coal seams, the high purity of the coal seams with minimal contamination from mud and sand, and the inability to find an analogous modern environment.

As the early geologists uncovered this disturbing array of anomalies that contradicted their expectations, they resorted to secondary hypotheses. It led to conflicts between the English-speaking geologists (of England and America) and the geologists on the Continent. While the hypotheses developed have today become part of the standard explanation for the origin of coal measure, they are still inadequate to account for the evidence and have in no way been resolved over time. Quite the contrary: the more the problem is studied (and despite a large quantity of solid work done to elucidate the geochemistry of the situation) the greater the apparent discrepancies seem.

This leads to the conclusion that the problem is with the interpretive paradigm. The predicament geologists have gotten themselves into over this origin question arises from their propensity to put forth qualitative and premature hypotheses. Lack of quantitative calculations, statistical tests, and experimentation is also a major factor. We are now at the place where we need to consider geological processes that are qualitatively different and of a larger scale than the pioneers of the discipline were prepared to consider. In other words, the paradigm needs updating.

Acknowledgement

This article has been kindly reviewed by Barry Lee Woolley. Joshua A. Woolley provided the reference information necessary for the cantilevered-beam-analogue-of-a-lycopod-trunk calculation.

References

1. Later, in the United States, geologist Alexander Winchell proposed the name "Mississippian" in 1869 for the mainly limestone Lower Carboniferous strata exposed along the upper Mississippi River drainage region, and after that, in 1891, Henry S. Williams suggested "Pennsylvanian" for the coal-bed containing Upper Carboniferous. These terms were subsequently used by American geologists and paleontologists in place of the one Carboniferous System used in Europe. Agreed-upon adjustments in stratigraphic boundaries have brought the Early Carboniferous and the Upper or Later Carboniferous into alignment with the Mississippian and Pennsylvanian, respectively.
2. Often times a major part of the plant which has become a form genera (viz. *Lepidodendron*) has come to designate the whole plant.
3. Williamson, C.W., A monograph on the morphology and histology of *Stigmaria ficoides*, *London Palaeontographical Society*, p. 12, 1887.
4. If a lycopod be modeled as a cantilevered 30-meter-long circular wood cylinder, it will fail in 130 km/hr [80 miles per hour] winds. The failure will not be in bending induced compression, but in the associated shear. The failure will be at its full circular base. This may be a hint as to why *Stigmaria* are usually separated from their fern tree trunks.There are a variety of empirical formulas that give the force of wind on a vertical cylinder, all of them giving nearly identical answers. One of the simplest is $F = APC_d$, where F is the force in pounds per square foot, A is the projected area of the item in square feet, P is the wind pressure in pounds per square foot given by $P = 0.00256\ V^2$, where V is the horizontal ideal sustained wind speed given in miles per hour, and C_d is 1.2 for a long cylinder (though more likely to be 1.0 for mature lycopods). If P and C_d were to be changed to $P = 0.004\ V^2$ and $C_d = 0.67$ (again for a cylinder),

this would take into account a 30% gust factor. (Though this empirical formula gives smaller values than the previous one, this seeming physical contradiction goes away when refined definitions of the different wind speeds are taken into account.)

A more involved formula explicitly taking into account the gust factor and an ‘exposure coefficient’ could be given, but the simplest (top) formula is sufficient for the purposes of this paper. (English units have been used, corresponding to civil engineering practice in the United States.) The lycopod or *Sigillaria* has been modeled as a 2.0-meter diameter, 30-meter-high right circular cylindrical column attached to its root system.

The formulas used for stress induced by bending and shear stress (as well as for maximum deflection) are found in: Timoshenko, S. and Young, D.H., *Elements of Strength of Materials*, 4th ed., D. Van Nostrand, New York, pp. 212, 107, 128, January 1962. The material parameters for wood were taken from Table A.2 on page 343 of the same work: the average of the listed properties for the various woods found in the table was chosen as representative. The indentations on all three layers of lycopod bark will decrease the bending and increase the resistance to failure by shear stress; this has not been taken into account in the calculations.

5. For French botanist and geologist Adolphe-Theodore Brongniart proposing *Sigillarias* and *Lepidodendrons* were aquatic see *More Letters of Charles Darwin*, vol. 2, Johnson Reprint Corporation, New York, 1972 after the original in 1903, Letters 552, 553, and 555 to J.D. Hooker of May 1846; 2 June 1847; and 22 May 1860, respectively. Binney took up this same argument in Binney, E.W., *The London, Edinburgh, and Dublin Phil. Mag*., vol. **24**, p. 173, 1844; and Binney, E.W., On the Origin of Coal, *Mem. Literary and Philosophical Society of Manchester*, volume **8**, pp. 148–193, 1848.
6. Currently *Stigmaria* is considered the root system of the *Lepidodendraceae* (*Lepidodendron*, *Lepidophloios*, *Diaphorodendron* and *Paralycopodites*) and *Sigillariaceae* (*Sigillaria*). It is considered by some as a shoot modified for rooting.
7. Lesquereux, L., *Description of the Coal Flora of the Carboniferous Formation in Pennsylvania and Throughout the United States*, vol. 1, Board of Commissioners for the Second Geological Survey, Harrisburg, PA, pp. 510–513, 1880.
8. Bouska, V., *Geochemistry of Coal*, Elsevier Scientific Publishing, New York, p. 25, 1981 states “Coal deposits corresponding to present day highmoor bogs have not yet been found. Highmoor bogs with their growth of Sphagnum, moss, various grasses and heath occur in cool northern and mountainous regions. They are known from western Wales and northern and central England.” He asserts that there is no real equivalent of a modern tropical peat-to-coal sequence anywhere in the world today.
9. Oliver, F.W. and Scott, D.H., On the structure of the Paleozoic seed *Lagenostoma lomaxi*, with a statement of the evidence upon which it is referred to *Lyginodendron*; in: *Philosophical Transactions of the Royal Society of London*, **197B**:193–247, 1904.
10. Dawson, J.W., *Acadian Geology*, 2nd ed., Macmillan and Company, London, pp. 205–206, 1868. The lycopod periderm (bark-like tissue) was waterproof and decay resistant. This would have been of great advantage in a multilayer silvomarine environment.
11. Lyell, C., *The Student’s Elements of Geology*, Harper, New York, 1871.
12. Martin, E.A., *The Story of a Piece of Coal: What It Is, Whence It Comes, and Whither It Goes*, G. Newnes, London, p. 20, 1896: “each time the land was raised above the sea and the forest again grew, the contour of the land was very similar.” Concerning coal-measure sandstone wedges all pointing in one direction: “this is just what we do not find, for instead of it, the direction of the wedge-shaped strata varies in almost every layer … inference is that it was well within the sphere of influence of numerous streams and rivers, which flowed from every direction. … sandstone was originally formed in a closed sea or large lake, into which numerous rivers flowing from every direction poured their contents.”
13. Martin, ref. 12, p. 21.
14. Martin, ref. 12, p. 22.
15. Martin, ref. 12, p. 19.
16. Dawson, J.W., Regarding the drifted trunk deposits, *Quart. Jour. Geol. Soc. London* **10**:13–14, 1854.
17. Three of the thirty-five (or 8.6%) of the layers at the Joggins site had these terrestrial fossils present. Ferguson, L., *The Fossil Cliffs of Joggins*, Nova Scotia Museum, Halifax, Nova Scotia, p. 332, 1988.
18. The concept of facies, that is, the idea that two dissimilar parts of one lateral stratum were deposited next to each other as a result of natural, observable processes, was developed by Amanz Gressly (1814–1865).

    The author has seen, in the Rhode Island Formation at the Masslite Quarry in Plainsville, MA, the abrupt termination of Carboniferous and coal layers. This includes what appears to have been the diapiric (pushed up) puncturing of the layer above it by a ripped but intact shaley coal layer. (E.g. the layer quarried between December of 2005 and March of 2006.) Researcher Austin, S.A., *Depositional Environment of the Kentucky Number Twelve Coal Bed (Middle Pennsylvanian) of Western Kentucky, with Special Reference to the Origin of Coal Lithotypes*, Ph.D. thesis, Pennsylvania State University, PA, 1979 commented on the parting of coal layers in Kentucky, United States of America.
19. Kuntze, O., *Phytogeogenesis: Die Vorweltliche Entwickelung der Erdkruste und der Pflanzen in Grundzugen*, P. Frohberg, Leipzig, Germany, 1884.
20. The author’s examination of the organic remains and mineral content of siderite nodules in shale below the Middle Kittanning Coal in western Pennsylvania fixed the environment at euxenic marine (Eh of –0.2 volts and pH of 8.1).

    These conclusions (–0.2 volts for Eh and 8.1 for pH) were based on the examination of the phase diagrams for the following minerals in a siderite concretion containing a *Calamites* section, a crinoidal columnal, and a shell fossil: siderite, pyrite, chalchopyrite, galena, covellite and cerrussite. Krauskopf, K.B., *Introduction to Geochemistry*, McGraw-Hill, New York, 1979, and Garrels R.M. and Christ, C.L., *Solutions, Minerals, and Equilibria*, Harper and Row, New York, 1965. Considerations of the likely variance to be seen in them by changes in molality and chemical species present were taken into account. The diagrams for Cu-Fe-S-O-H at 25 °C and one atmosphere total pressure with dissolved sulfur being anywhere from 0.0001 to 0.1 molality have several extremely narrow, adjacent stability regions for the existence of pyrite, marcasite, covellite and chalcopyrite. As if to emphasize the fact that all geochemical reactions are local, concretions within a meter of each other horizontally (i.e. at the identical stratigraphic level) would randomly have galena, pyrite, and chalcopyrite at their core at the Portersville, PA fossil site, possibly related to the original organisms that decayed or the bacteria allegedly responsible for this taphonomy.
21. In studying a washed in peat deposit in southern Florida, a researcher reported in 1970 that a thin section of it resembled thin sections of Carboniferous coals rather than the thin sections of *in situ* deposits he studied. “A peculiar enigma which developed from study of the allochthonous peat was that vertical microtome sections of this material looked more like thin sections of Carboniferous coal than any of the autochthonous samples studied.” Cohen, A.D., An allochthonous peat deposit from Southern Florida, *Geological Society of America Bulletin* **81**:2477–2482, 1970.

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