The Proceedings of the International Conference on Creationism

Volume 8
Print Reference: Pages 277-286

Article 17

2018

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Recommended Citation
Austin, S.A., and R.W. Sanders. 2018. Historical survey of the floating mat model for the origin of Carboniferous coal beds. In Proceedings of the Eighth International Conference on Creationism, ed. J.H. Whitmore, pp. 277–286. Pittsburgh, Pennsylvania: Creation Science Fellowship.

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HISTORICAL SURVEY OF THE FLOATING MAT MODEL FOR THE ORIGIN OF CARBONIFEROUS COAL BEDS

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ABSTRACT

For three hundred years geologists and paleobotanists have been attempting to describe the process that deposited plant material that formed Carboniferous coal beds. Autochthonous and allochthonous explanations in the early Nineteenth Century showed how scientific methodology becomes involved in coal interpretation. Autochthonous modelers used the paleobotany-strata-petrology-environment method to argue that coal is a terrestrial swamp deposit. Allochthonous modelers used the petrology-strata-paleobotany-environment method to describe coal as a subaqueous deposit. The two methodologies are best displayed at the end of the Nineteenth Century in the consensus autochthonists versus the French School allochthonists. Three depositional models have been offered for the origin of coal: (1) peat swamp model, (2) drift model, and (3) floating mat model. Many paleobotany questions about lycopods and tree ferns had not been solved at the end of the Nineteenth Century, but the "floating mat model" offered a very robust path to direct research. Unfortunately, at the beginning of the Twentieth Century when the uniformitarian paradigm prevailed, the floating mat model was intentionally suppressed. Now new data from coal petrology indicate that Carboniferous coal is detrital having accumulated underwater, not as a terrestrial swamp deposit. New data and methodology from paleobotany (Sanders and Austin, 2018) show lycopsids and tree ferns were capable of forming living floating mats able to support the trunks. Paleobotany of coal plants should now be best understood as supporting a floating raft that deposited the detritus that now forms Carboniferous coal beds. We present here for the first time a three-hundred-year historical survey of the notion that coal accumulated from floating vegetation mats.

KEY WORDS

floating mat model, origin of coal, Carboniferous paleobotany, paleoecology, tree lycopsids, *Lepidophloios*, *Stigmaria*, tree fern, *Psaronius*, sedimentary process, detrital deposition, coal petrology, stratigraphy, depositional environment.

INTRODUCTION

Coal is the rock formed from accumulated and altered plants. For 300 years coal has been recognized to have been derived from a material resembling modern peat. How did that accumulation occur to form prominent Carboniferous coal beds? This is a most interesting and controversial question with 300-year legacy. It is not a trivial question. As the most abundant fossil fuel, coal continues to be a primary source of energy, metallurgical coke and petrochemicals. Understanding coal utilization benefits from understanding coal's formative processes. Vegetable, mineral and animal components within coal make it the most complex sedimentary rock. Those who focus study on this most complex rock are called coal petrologists. Complexity means coal contains an enormous amount of information. For hundreds of years geologists have been offering explanations of the origin of Carboniferous coal. That interest and controversy associated with coal's legacy continues actively among geologists to the present.

Among geologists, two broad categories of depositional models for Carboniferous coals have been debated for three hundred years. The prevailing uniformitarian explanation of coal formation supposes coal beds to be authigenic and autochthonous (manufactured through a soil-forming environment from plants grown in place) and deposited within coastal swamps, delta plains or river levee environments. The enduring catastrophist explanation, never silenced during hundreds of years, supposes coal beds to be detrital and allochthonous (water-borne detritus transported to the submerged surface of sedimentation) and, likely, associated with rafts of floating vegetation. We present here for the first time a three-hundred-year historical summary of the notion that coal accumulated from floating vegetation mats.

ROOT OF CONTROVERSY

Advocates of autochthonous Carboniferous coal devised paleoecological interpretations of plant fossils, especially rootlike structures of lycopods. These paleobotanical ideas are placed within strata sequences to assign the different rock layers to terrestrial swamp, floodplain and levee environments. Among the most famous early advocates of autochthony of Carboniferous coals (arguing from paleobotany through stratigraphy and petrology to paleoenvironment) were the field geologists Charles Lyell and John Dawson. Lyell (1855) and Dawson (1854) examined the rootlike fossil named *Stigmaria* in sandstones and shales at Joggins in Nova Scotia. They also described fossil lycopod trunks standing upright in shale strata, but they didn't find them within coal beds. These upright trunks were interpreted to have formed *in situ* within fossil soils containing *Stigmaria*, and the associated coal beds were considered to be autochthonous, formed in large, topographically elevated, freshwater mires. Later at Joggins assemblages of upright trunks were supposed to represent *in situ* "fossil forests" on an elevated area. Among the autochthonous

modelers of the origin of Carboniferous coal, the priority is coal paleobotany, not coal petrology. The autochthonist explanation of the origin of coal became the dominant view in the Twentieth Century following the methodology of Charles Lyell. Gastaldo (1984), McCabe (1984), Scott (1998), and O'Keefe et al. (2008) are modern advocates of autochthony using the "paleobotany-strata-petrology-environment" methodology.

Advocates of allochthonous Carboniferous coals focused on coal petrology. Allochthonists studied coal composition, structure and texture under the microscope from coal thin sections. Two classic allochthonists were the French petrologist/paleobotanists Cyrille Grand'Eury (1882) and Henry Fayol (1887). Interpretations made on fine-textured cannel coal were extended into what are called coarser-textured and banded humic coal (lithotypes clarain and vitrain). Coal did not compare well with modern *in situ* swamp peat. They saw detrital textures, oriented plant structures and very thin shale partings dominating thin sections without rooting evidences within the original peat. Strata associated with coal beds also seemed to indicate submerged conditions. Assigning only secondary importance to the paleobotany, early allochthonists understood *Stigmaria* to be a solitary, prone-floating stem with leaves, that when deposited on sediment, became able to sprout an upright lycopod trunk. Environments of plant growth were generally envisioned on terrestrial upland surfaces. Eroded plant detritus was transported in rivers as dispersed grains and settled through water in lakes, submerged parts of deltas or marine estuaries. A vigorous "French School" of allochthonist thought continued through the Twentieth Century and remains with us today. An English publication of recent French-School coal petrologists is very readable (Ligouis and Doubinger, 1991). This way of thinking about the origin of coal was called the "drift model." Both early and later allochthonists of the French School used the "petrology-strata-paleobotany-environment" methodology to understand the origin of Carboniferous coal.

About the same time as the French School of allochthonists was developing subaqueous notions for coal deposition and elaborating "drift model," another group of allochthonists appeared. This second group of allochthonists was uneasy about coal plants being grown on upland terrain and then transported as debris by rivers to lakes or deltas. This second group proposed coal-forming plants existed on large floating rafts of vegetation and that coal was deposited as vegetation sank. Three prominent advocates are German botanist Otto Kuntze (1895), the British-American engineer and geologist William Gresley (1894a), and the Cambridge University paleobotanist Albert Seward (1895b). The explanation offered by this group is called the "floating mat model" for the origin of coal, and the history and observations leading to this model appear in the following pages. We will learn that the "drift model" and the "floating mat model" of allochthonists use the "petrology-strata-paleobotany-environment" methodology to understand the origin of Carboniferous coal.

What can be said in summary about the three-hundred-year debate about the origin of Carboniferous coal? There are three explanations: (1) peat swamp model, (2) drift model, and (3) floating mat model. One observation is agreed upon by the three camps – autochthonists with their peat swamp model occupy the higher ground, define the terms of debate, and bring paleobotany to the front line of the debate. Gastaldo (1999) defends autochthony calling it "Empirical science versus the diluvialists." How strong is the evidence from upright fossil trees? Many examples of Carboniferous forests supposed to have grown in place have appeared in the literature (surveyed in DiMichele and Falcon-Lang 2011, Thomas and Seyfullah 2015). Could those "forests" instead be floated and grounded mats of vegetation? What about those lycopod "roots" in strata around coal beds? Is the iconic coal fossil *Stigmaria* really indisputable evidence for growth in place of roots in fossil terrestrial soils? All these questions show us that there is a critical need to revisit lycopod and tree fern anatomy. Paleobotany needs to be considered in detail, and attention needs to be directed at alternate depositional models. That will direct our clear thinking to make progress in understanding the origin of coal.

SEDIMENTATION FROM FLOATING MATS

For thousands of years people have known about modern wetland areas where mosses, reeds, shrubs and trees are attached to a peat foundation that floats freely on water. God asked Job to marvel at Behemoth, the large animal that lived among floating plants: "Under the lotus plants he lies down, in the covert of the reeds and the marsh. The lotus plants cover him with shade; the willows of the brook surround him" (Job 40:21,22). Plato and Pliny inform us of floating forests being a special human fascination, making a deep impression on Greeks and Romans with awe and wonder. They have been featured in the popular press (Figure 1). Scholars have called them "floating mats," "floating vegetation islands," or even "floating forests." Botanists, ecologists and geologists are increasing our knowledge of these unusual habitats (Van Duzer 2004, Azza et al. 2006, Volkova 2010, de Freitas et al. 2015). They are best known within big river systems (e.g., Mississippi, Congo, Nile, Amazon) and within most big coastal freshwater wetlands (e.g., Dismal Swamp, Okefenoke, Everglades). Free-floating *marine* islands with trees have been reported, but, today, are very rare. To this diverse inventory of floating botanical material can be added the non-living floating biomass. A prominent example is the floating dead conifer log mat on Spirit Lake after the 1980 eruption of Mount St. Helens.

Our thinking about floating vegetation can be sharpened by one modern example from South Sudan. "The Sudd" is the 22,000-square-mile wetland that blocks the White Nile's northward flow ("Sudd" is the Arabic word for "barrier" or "obstruction"). Long-term channel stability does not exist on this segment of the White Nile. That's why Emperor Nero's Roman soldiers in 61 AD could not penetrate the Sudd to explore the source of the Nile. During the dry season, grounded peat and floating peat are stabilized in gridlock between river channels. As water rises during the rainy season, however, grounded peat returns to floating, and floating peat is released from barriers to drift by current into enlarging channels. Quickly distributed floatant moves as rafts to chokepoints in big channels where it stops again in gridlock. Water flow is then diverted to form new channels. It is easy to recognize from this example how allochthonous processes even dominate modern wetlands.

Little is known about sedimentation beneath floating mats, but it likely resembles lake deposits (Moore 1989), and could include

broken mats or even docked ("beached") mats. Over the three hundred years, scholars have pondered the possible role that floating vegetation may have had in forming coal beds. Austin (1979) introduced the term "floating mat model" in reference to the origin of coal. The term "floating mat model" seems broad enough to include deposits from both living or dead floating vegetation, and general enough to include various vegetation types ("algal mats," "floating marshes," and "floating tree islands"). The term "floating mat" directs our thoughts first toward the buoyant substrate of the raft of vegetation, which is likely the dominant source of detritus.

EARLIEST THOUGHTS ON FLOATING MAT MODEL

The French botanist Antoine de Jussieu (l718) was digging fernlike impressions and marine shell fossils from Carboniferous shale near Saint Chaumont. As he continued digging the fern impressions became more black and bituminous as they passed into the bed of coal. He believed these impressions and coal represent tropical plants unlike those in France today. He supposed that tropical plants were picked up by flood waters, floated great distance when the ocean covered the continent, and finally deposited in high country in France. He noted the texture of plants in coal resembles the flat lying fragments on the floor of the French herbarium. Jussieu was one of the earliest advocates of a floating mat model for the origin of coal.

Among the earliest to argue strenuously for the vegetable origin of Carboniferous coal were the British mineral surveyor John Williams (1810) and the British surgeon and paleontologist James Parkinson (1811). They disputed with James Hutton and John Playfair (the authors of uniformitarian theory) who supposed coal to be formed, not from vegetation, but from asphalt impregnating mud. Williams (1810) believed coal to be made from transported timbers: "I am of the opinion that the antediluvian timber floated upon the chaos or waters of the deluge, … and that during the height of the deluge and the time in which the greatest part of the strata were forming, the timber was preparing and fitted for being deposited in strata of coal." Parkinson (1811) added to Williams by stressing that woody particulates (not timbers) formed coal, and that the original substance of coal resembled modern peat. Parkinson described in extraordinary detail what he calls "large floating islands" associated with modern swamps. These islands form in lakes when submerged peat breaks loose and floats abruptly to the surface. He knew that new vegetation could enlarge floating peat by plant growth, but recognized that floating islands generally break apart and are dispersed as fragments on the surface of modern lakes. Parkinson reasoned how coal would be deposited during the catastrophic deluge in *reverse* of the modern floating island scenario. Dispersed floating woody fragments were once collected to form a raft of floating peat, which later sprouted vegetation, and, which during the deluge, was transported and sank to make coal. It was further refinement of the floating mat model. Also, as the famous professional surgeon, Parkinson was first to described the neuro-muscular disorder later called Parkinson's disease, and, through surgery, was first to demonstrate that severe appendicitis is caused by perforation at the surface of the human appendix.

The history of the floating mat model resumes with the work of the Scottish stratigrapher Roderick Murchison (famous among geologists for defining the Silurian System). Murchison (1845, p. 114) described the Carboniferous coal of the Donetz Basin in Russia and wrote about its formation "… by the sinking into the adjacent sea of floating masses of matted earth and plants." Murchison imagined marine floating mats: "… when the bottom of the sea was spread over with the detritus of matted and

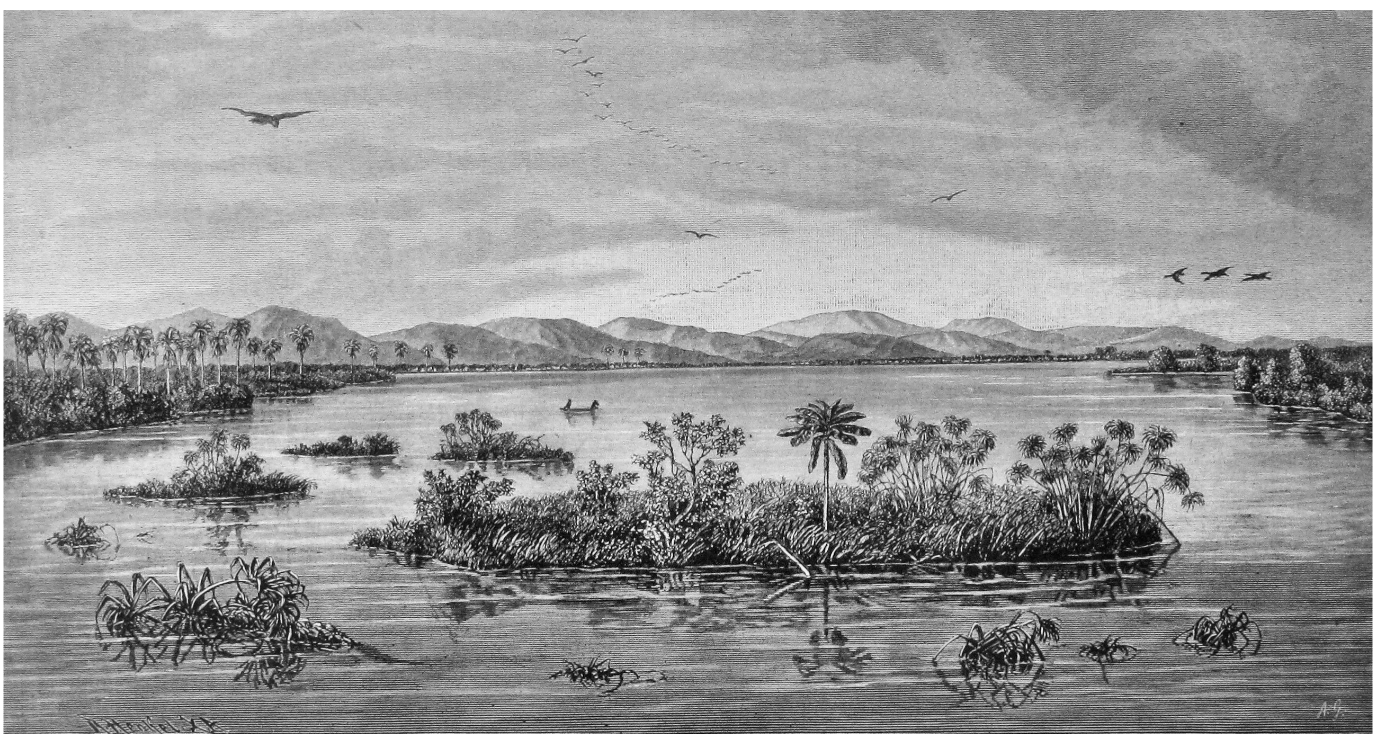

Figure 1. Floating islands on the Congo River, a print by A. Goering, published in 1883 by *Die Gartenlaube*, Germany's first mass-circulation newspaper. Circulated from Leipzig, hometown of Otto Kuntze, this illustration and its artist inspired Kuntze to publish in 1884 his "floating forest" illustration that is Figure 2

broken plants, washed into it by inundations or freshes of former rivers, that the heavier earthy matters which accompanied such accumulations (in the same way as in the floating islands or snags of the great American rivers), sank to the bottom, whilst the lighter plants floated and formed the upper stratum…." Murchison's straightforward mat description influenced German paleobotanist Heinrich Göppert (1848) who also favored sea-bed accumulation of coal. Like Murchison, he was impressed with the vast extent and continuity of structure within coal. Göppert found it difficult thinking of such a mass being floated in all at once, yet coal's continuity of structure seems explainable by no other means. In general agreement with Murchison, the German mineralogist Carl Naumann (1854) understood rivers to be very important in bringing floating vegetation to the ocean where it collected into rafts that washed up on shore.

EARLY FORMULATION OF THE FLOATING MAT MODEL

The Swiss-American paleobotanist Leo Lesquereux left a profound influence on understanding peat and coal. He has been called the father of American paleobotany. As a young man in Europe he specialized in botany and ecology of European peat bogs including floating peat (what he often called "floating carpet" or "mat"). In 1848 he accompanied Louis Agassiz by moving to the United States, where he worked for state geologic surveys in Pennsylvania, Ohio, Indiana, Illinois and Kentucky to describe Carboniferous fossil plants. Lesquereux (1870, p. 452) wrote, "It is my belief, the genus *Stigmaria* does not represent tree roots, but floating stems, of which species of the genus *Sigillaria* constitute the flowers or fruit-bearing stems." Concerning the ontogeny of *Stigmaria* growth, Lesquereux affirmed the opinion of Goldenberg, "The stems could grow independent for a considerable length of time as floating and sterile, or bear erect flowering stems or trunks when the ground was solid enough to support trees" (Lesquereux 1880, p. 512). In subsequent publications he sketched a fresh-water depositional model for Carboniferous peat. Lesquereux (1885, p. 120) wrote, "Most of the land surface was then a vastness of swamps, in which the first growth, generally floating or creeping plants, was essentially composed of a particular species, the *Stigmaria*, whose immensely long stems ... were woven together, like the thin, matted, floating stems of the *Sphagnum* of the present age, into an immense woven mat or thick carpet, over which the luxuriant land vegetation of the coal soon spread itself." Coal formed from the raft as it sank of its own weight into the water beneath and became a deposit wholly submerged. In addition to floating mat deposits on submerged surfaces within the fresh-water swamps, Lesquereux also imagined *in situ* peat deposited on upland surfaces.

As Lesquereux was linking observations that favored coal from floating mats, the French School of coal petrologists (Grand'Eury, 1882; Fayol, 1887) suggested the Franco-Belgium coal field was a series of lakes into which drifted detritus was accumulated to form multiple coal beds. A French railway engineer Ludovic Breton (1885) disagreed. Breton proposed that the Franco-Belgium coal beds were deposited from floating islands. Each coal bed was accumulated in fresh water from a floating vegetation island that grounded on the surface of sedimentation. Had Breton supposed coal to be *detritus settled underneath* a floating mat, his explanation might have impacted the French School. Instead, Breton's work was largely ignored.

The British and American mining engineer and geologist William S. Gresley likely had more direct experience observing British and American Carboniferous coal than any of the geologists or botanists mentioned previously. He was the first to document coal balls in North America. Also, he can be called the father of coal petrology in North America. Short geologic papers by Gresley (1885, 1887, 1894a, 1894b, 1899), showed that coal composition, coal parting structure, coal underclay, and coal roof-bed architecture argue against coal bed formation in swamps. His competence in coal is demonstrated by perceptive questions (Gresley 1894b). How could a single three-eighths-inch-thick shale parting be deposited within the Pittsburgh Coal Bed throughout a 15,000 square mile area? Even more important to Gresley was the preservation question. How could the continuity of that parting be preserved as an equally widespread bench of vegetation was formed directly above that parting? He was diligent in search of *Stigmaria* associated with Pittsburgh Coal, and he finally found one broken and transported fragment near Elizabeth, Pennsylvania, the first to be reported or published throughout the 15,000 square mile area of mining within Pittsburgh Coal. Beginning with the petrology of the coal bed, he reverse-engineered the depositional environment: "... the evidence points to the formation of coal on the floor of an expanse of water, by vegetable matter sinking down from floating 'islands' of vegetation, which may have been of very large size" (Gresley 1894a). Like Göppert, Gresley marveled at the immensity of scale. Gresely (1894b) was not settled if it was a marine or freshwater condition, but was certain "... vegetation of such character as thrived in luxuriant profusion upon the surface of the water ... living afloat and dying and decaying, falling through the water." He agreed with the French School of allochthonists that coal was a *detrital* accumulation, but the French School, especially after Breton's work, did not postulate sedimentation from the mat.

The German botanist Otto Kuntze (1884, 1895) benefited greatly from both Naumann's and Lesquereux's ideas, but apparently Kuntze had no exposure to Gresley's short publications or Breton's monograph. Kuntze classified peat-forming environments after Naumann, but he went significantly beyond Lesquereux in stressing the importance of floating vegetation mats in peat deposition. Lesquereux and Kuntze were both botanists approaching the floating mat idea. They both recognized *Stigmaria* to be a floating stem with "water leaves" (definitely not a root in soil). Lesquereux applied the mat idea just to limnic fresh-water peats and the resulting interpretation of cannel coal, while Kuntze supposed widespread *marine* floating mats (see Figure 2) that could deposit both cannel coal (homogenous, fine lithotypes) and humic coal (banded, coarser-textured lithotypes). Kuntze supposed marine-influenced humic coals of England and United States (what Naumann called paralic coals) to form from a marine forest living on a floating peat substrate.

Kuntze and Lesquereux differed somewhat on the origin of underclay, but both believed that a peat mat sank *en masse* in an aqueous environment onto the submerged clay layer to form a coal bed. Kuntze postulated a Carboniferous marine floating forest biome with lycopod trees being only one of several mat species.

Both distanced themselves from the French allochthonists who thought about coal being an aqueous accumulation of transported terrestrial-forest detritus (what petrologists call a "allochthonous, detrital texture"). Lesquereux and Kuntze did *not* favor detritus being shed from the mat to form a submerged peat layer as postulated by Gresley. Both recognized the deficiency of phytogenic sediment being moved out of modern terrestrial swamps by modern rivers, an observation they understood to favor the mat idea.

The turn of the century was a critical junction for the floating mat model. Lesquereux, Breton, Kuntze and Gresley had developed the concept. Support came from Albert Seward (1895a, b), the British paleobotanist at Cambridge University: "…the weight of evidence seems to tip the balance of opinion very materially towards the theory of drifting, and subaqueous sedimentation, for the majority of Paleozoic coal seams." Seward liked the floating mat model and acknowledged the model of Lesquereux and Gresley, but Seward did not mention Breton or Kuntze. Alfred Lane (1902), the state geologist of Michigan, extensively reviewed Kuntze's terminology and model applying it to Michigan coal beds. Lane mentions paleontologist Carl L. Rominger, another state geologist of Michigan, who endorsed the *Stigmaria*-floating-stem theory of Lesquereux and Kuntze.

An interesting episode occurred at the annual meeting of the Iron and Steel Institute in 1900. That is where state-of-the-art metallurgy, manufacturing technology and natural resources were discussed. Prominent on the meeting program was the session in Bradford, England titled "The Origin of Coal." We know about several of the presenters and their papers from the anonymous "notes" of the meeting that were published in the Journal after the meeting (no authors' papers were published). According to the notes (Anonymous 1900) the prominent British geologist Aubrey Strahan discussed "rooted" underclays, erect tree trunks in sandstone and persistent partings within coal, what are called "clear proof of a drifted origin" and evidence of "subaqueous deposits." Also at the 1900 meeting was the British paleobotanist from Cambridge University A.C. Seward who discussed subaqueous deposition of plant debris: "Hence he [A.C. Seward] thought that the seams were not the result of growth in one place, nor of drifting, but of the accumulation of vegetable *debris*, derived chiefly from plants growing on the surface of large lakes and pools near the borders, where they died and were carried out by gently flowing water and sank to the bottom over the whole water area" (Anonymous 1900, p. 432). The meeting notes describe some of the interesting discussion as replies, proving that scientific model building was occurring by critical evaluation of evidence.

By 1900 there were actually three general explanations of the origin of coal: (1) swamp model, (2) drift model, and (3) floating mat model. Underappreciated was the problem resident in all explanations of coal, not just within the floating mat model, of the immensity of scale that seemed to be required. Gresley, who appreciated the matter well, was uncomfortable in imaging the Pittsburgh Coal being accumulated under a mat expansive through a minimum area of 15,000 square miles. Göppert following Murchison's idea, also struggled with scale but had to admit that is what the strata seem to indicate. Strahan's sedimentation proposal obviously had to explain very thin strata of wide extent. This can be called the "its-too-big problem."

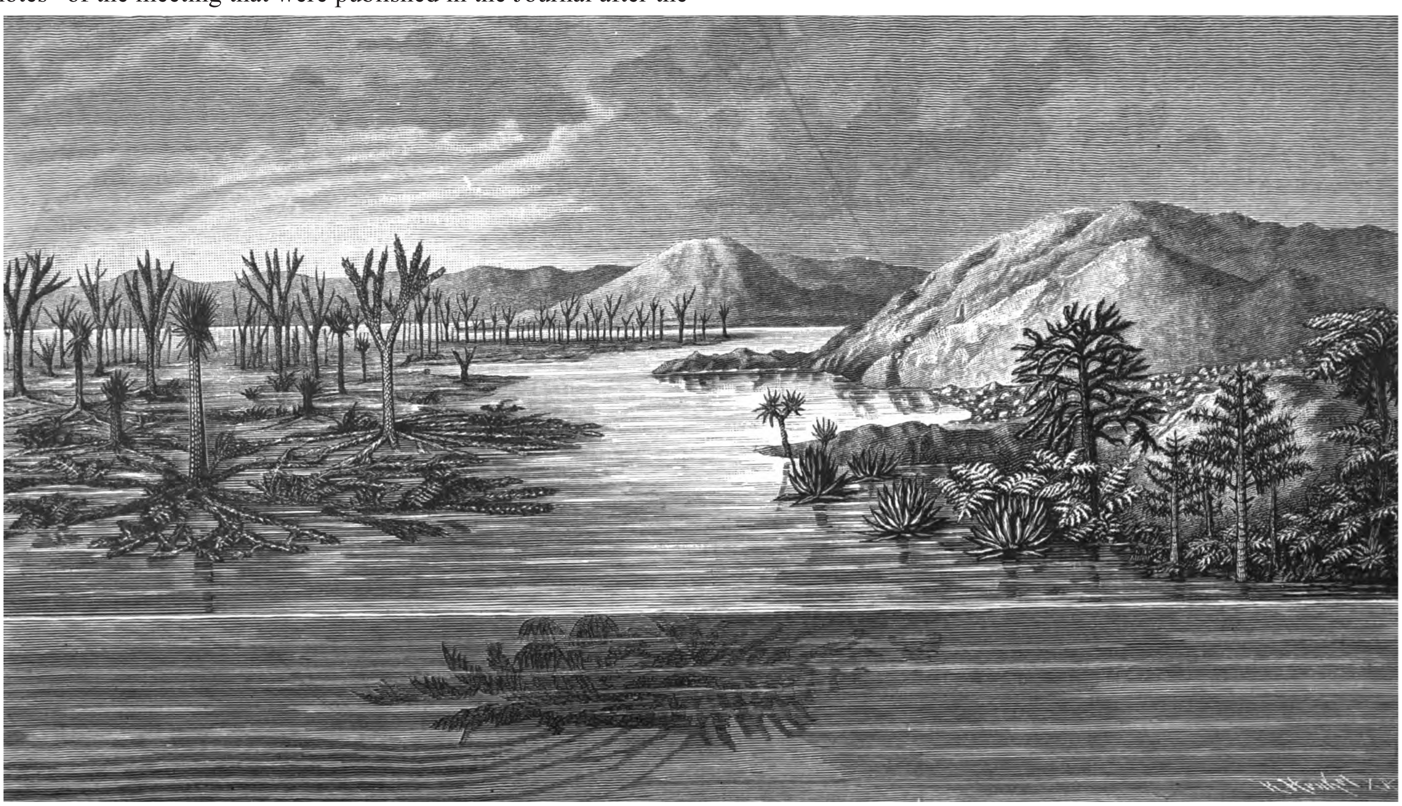

Figure 2. Floating mats according to Kuntze (1884). Ancient tree islands were constructed by lycopods that grew on top of the water (left center), and occasionally sank (as depicted in lower center).

LATER HISTORY OF THE FLOATING MAT MODEL

The history of the floating mat model resumes at the start of the Twentieth Century with unfortunate turn of opinion. The controversy concerning the origin of coal had been skillfully summarized by Cambridge geologist Newell Arber (1912). He outlined all the controversial topics, then wrote: "…each seam of coal must be examined, studied, and judged entirely on its merits." The new generation, however, did not follow his advice. This was the time when uniformitarian doctrine was making its transition to become geologic orthodoxy. It was not just a debate about fossil roots and sedimentary process. The paradigm system within all of science was being negotiated, likely behind closed doors, with critical decisions being made. Geologists recognized "blank checks" with nearly unlimited funding in the geologic time account. Catastrophist models didn't use much time, and were being superseded. As a result, allochthonous theory of coal formation was being challenged, marginalized, or even deliberately suppressed. The floating mat model was ignored.

Several developments likely assisted the uniformitarian reform movement. We speculate here on these causes. This was a time of significant change with increasing controversy in politics, religion and science. People were not inclined to critical discussion or debate about the two-hundred-year-old esoteric topic of environments of coal deposition (distractions not needed, as prime concerns are world wars, technology, mechanization, eugenics, women's rights, Marxism and Darwinism). Specialization in sciences also served as distractions. Coal petrology proved extremely useful and saw its application in coal technology and metallurgy. Paleobotany was distracted from global critical discussion by discovery of coal balls which refocused Carboniferous research to details of phylogeny and plant anatomy. Then, with World War 1, petroleum and natural gas became the fuels of choice. Almost all the coal geologists at U.S. Bureau of Mines were hired by new oil companies. The smartest people left to do other things!

In 1913 the federal government became involved in the Carboniferous coal debate with the publication of U.S. Bureau of Mines Bulletin 38 "The Origin of Coal" (White and Thiessen, 1913). David White, Director of the U.S. Geological Survey, was the paleobotanist and Reinhardt Thiessen was the coal petrologist. The impact of Bulletin 38 was enormous. On the controversial questions, White and Thiessen offered their own interpretation of the origin of coal within the overall framework of emerging uniformitarian orthodoxy, without alternate models. It was shrewd use of opinion and government position to defuse debate. However, concerning *Stigmaria*, it was not an opinion – it certainly was a soil rooting organ of terrestrial trees. White introduced and dismissed the floating mat controversy with a *single* opinion sentence: "In none of the important and widely extended coal beds examined by the writer has he observed any lenses or intercalated bodies of coal that may be interpreted as masses, floating islands, or rafts of vegetation somewhat abruptly submerged, in accordance with the hypothesis proposed by numerous writers" (White and Thiessen 1913, pp. 63, 64). The names of the "numerous writers" are not mentioned so that the history can be ignored. White and Thiessen's opinions about what they have not seen changed to certainty in later retelling of the story: "White and Thiessen studied the origin of coal; their book on coal (published in 1913) disproved the allochthonous origin of coal, the popular theory of the time." (Lyons and Morey 2006, p. 55). White and Thiessen didn't disprove allochthony, they simply ignored it.

American geologist John Stevenson (1913) extensively reviewed the history of autochthonous versus allochthonous coal, putting a decidedly autochthonous spin when reviewing the story. Stevenson's spin is seen in how he deals with A.C. Seward (1895a,b), his contemporary and peer at Cambridge University, who also published a historical review of allochthony and autochthony. Stevenson's 530-pages ignores that prominent work of Seward, but recognizes Seward in one sentence about a trivial matter of plant anatomy. Stevenson's summary is another opinion statement: "…to this writer, it appears certain that the path marked by allochthony ends in a *cul-de-sac*, walled with contradictions; and that farther investigation along that path will be fruitless…." (Stevenson, 1913, p. 486). Today, over one hundred years later, we can ask questions about Stevenson's two opinions. Is it certain that allochthony ended a hundred years ago in a *cul-de-sac* walled by contradictions? Did allochthony as a scientific explanation continued to remain fruitless?

Statements of opinion, not careful comparison of models, became the enterprise of the new science. Old opinion (allochthony) was superseded uncritically and deliberately by the new opinion (autochthony). Then, within a few years, opinions were no longer stated as opinions. They were stated as facts while a new generation of geologists was in training. That is how Carboniferous coal became widely associated with the autochthonous model in the Twentieth Century. The new consensus attributed upright tree fossils within strata to be standing forests that grew *in situ*, not remnants of floating mats deposited after transport. *Stigmaria*, in the new consensus, became *in situ* roots that penetrated terrestrial soils. Therefore, by close paleobotanical association, coal became a terrestrial deposit, not a subaqueous sediment. Notice the deliberate steps of the new methodology: paleobotany-stratigraphy-petrology-environment.

However, throughout the Twentieth Century, many paleobotanists and geologists understood coal to have formed from subaqueous plant detritus. In quick response to uncritical acceptance of autochthonist opinions (e.g., White and Thiessen 1913, Stevenson 1913), the Harvard plant physiologist E. C. Jeffrey (1915) and his graduate student Carl Forsaith (1917) documented the detrital textures of allochthonous modern peat in Florida and similar texture petrographically in Carboniferous coal. Jeffrey (1924, 1927), Francis (1961), Coffin (1969) and Cohen (1970) were noteworthy in critical reevaluation as autochthonous evidences were being overstated. These allochthonists directed attention to flaws in the autochthonous model. Their work was largely ignored by autochthonists. Throughout this period no developed statement of the floating mat model appeared.

As graduate student in the coal petrology program at Pennsylvania State University, Steven Austin (1979) submitted a Ph.D. dissertation on the Paradise (Western Kentucky No. 12) Coal Bed. At the top of the coal bed Austin described petrographically nine lithotypes. Next, through a stratigraphic study of the nine

lithotypes, a single lithofacies picture was sketched for the top of the coal bed. Lithofacies analysis depicted in Figure 3 shows that marine limestone and shelly coquina lithotypes intertongue horizontally with bright, well-laminated coal lithotypes. Also, bright coaly sheets (the lithotype called vitrain) occur within and upon the upper bench of the coal. The vitrain sheets in shale have a flat surface that displays the unmistakable impression of lycopod bark. Microspores and tissue fragments of lycopods and tree ferns occur without vertical penetration of the coal vitrain sheets, without disruption of clarain lamination, and without breaking carbonaceous shale partings, appearing to falsify the peat swamp model for Paradise Coal Bed. These were some of the same petrographic observations of Gresley on the Pittsburgh Coal Bed. Encouraged by Gresley's interpretation, Austin proposed *living* lycopod trees composed a marine floating mat: "...lycopods were more tolerant to saline conditions and were capable of building stronger mats in the more wave-influenced areas...." (Austin 1979, pp. 346, 347). Not elaborating further on the ecology of lycopods living upon a floating mat, he simply supposed a variety of plants grew on the mat, mostly lycopods (especially *Lepidophloios*) and tree ferns (especially *Psaronius*). The coal bed formed as the floating mat moved and shed vegetable detritus that sank as particles onto the submerged surface as granular peat (as described by Gresley, not deposited *en masse* by sinking or beaching of the mat, as suggested by Breton and Kuntze). Austin (1979, pp. 334-347) introduced the term "floating mat model" for the origin of coal and left the terminology broad enough to include either living or dead mats. After graduate school, Austin continued study on the newly-formed, dead-conifer floating log mat at Spirit Lake north of Mount St. Helens (Austin 1991, Coffin 1987). He also studied the size and shape of bark sheets (the lithotype vitrain) in the top of the coal bed and in the overlying shale (Austin 1980).

LATEST DISCUSSIONS OF FLOATING MAT MODEL

A model of living Carboniferous floating forests in a creationist context was offered by paleontologist Joachim Scheven (1981, 1996). He proposed that lepidodendralean trees floated "on the surface of vast but shallow bodies of water" (Scheven 1981, p. 40) and "the floating coal forest communities stood on freshwater only" (Scheven 1996, p. 77). That is the marine floating forest biome developed by Kuntze. Scheven added to Kuntze that the tree trunks and rooting systems contained continuous cylindrical air cavities between the internal wood cylinder and the bark and, therefore, would be buoyant enough to float with the trunks upright in the air. Scheven's explanation has waters retreating as mats landed *en masse*. It differs from Austin's explanation of the Kentucky coal bed where the mat *rose* with the advancing marine condition as the mat shed *detrital* plant fragments.

Building from Austin and Scheven's ideas, paleontologist Kurt Wise (2003) enlarged the floating forest to be a part of a more inclusive Middle to Upper Paleozoic ecosystem. He says, "In a fashion analogous to the plants of a quaking bog, it is suggested that the floating forest biome grew out over the ocean through an ecological succession of rhyzomous plants of steadily increasing size generating and thriving upon an increasingly thick mat of vegetation and soil" (p. 371). Furthermore, Wise suggests, "… the floating forest biome may have floated atop marine waters and may have generated a fresh-water water table in the mat" (p. 377). Wise argues: "Nor does [evolutionary theory] provide explanation for the rhyzomous nature of arborescent lycopod 'roots' which do not seem as if they could penetrate traditional soils" (p. 377). So, presumably, the arborescent lycopsids either floated on a freshwater lens atop the mats surface or were enmeshed in very loose, freshwater-saturated surface of mud or peat.

The concept of a living floating mat habitat has received further favorable review. Wesley Bruce (2002) proposed how fresh water would stratify from salt water and be stable within the proposed marine floating mat. Joanna Woolley (2010, 2011a, 2011b) conducted mathematical modeling of the rhizomorph architecture, and believes that *Stigmaria* were very long, and through intertwining, substantially strengthened the mat. Like Scheven, Woolley believes a mat landed *en masse* to form a coal bed.

Geologist Tim Clarey (2015) is an advocate of the floating mat model for the origin of Carboniferous coal because he believes that dead lycopods were assembled into rafts and floated through the Flood (resembling the coal explanation of Nelson, 1931, p. 88). Understandably, Clarey has difficulty with the mechanical and ecological feasibility of the floating forest biome of Kuntze, Austin, Scheven and Wise. Clarey (2015) offers his model:

> These unique flora [i.e., lycopod forests] may have filled

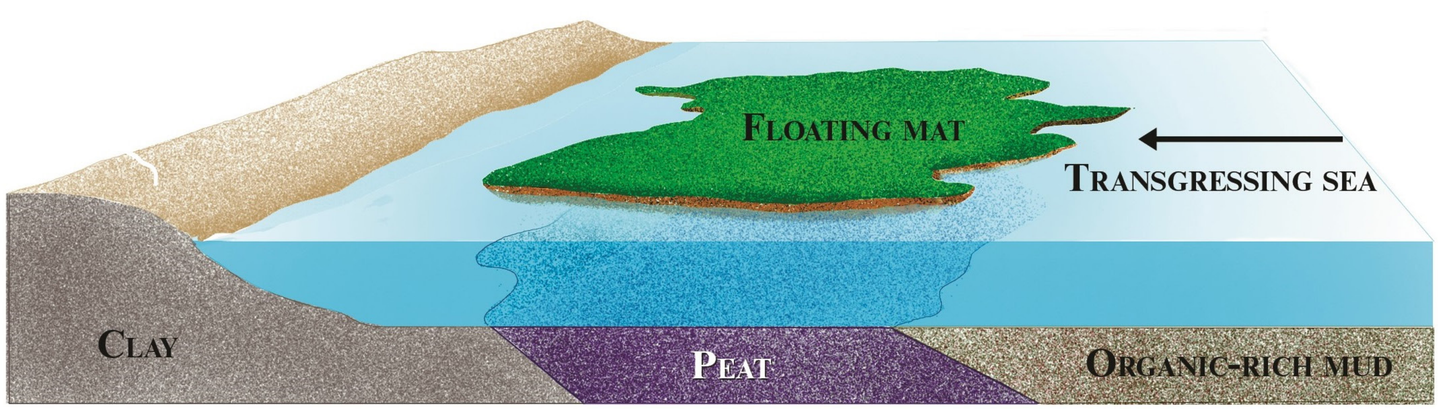

Figure 3. Austin's floating mat model for the Kentucky coal bed illustrated lithofacies associated with coal. Notice rising water produces intertonguing organic-rich mud (that became marine roof shale and limestone) with top of the detrital peat (that became bright coal lithotypes at the top of coal bed). Block diagram has *extreme vertical exaggeration* that greatly distorts the flatness of the boundary between peat and organic-rich mud.

> the outer edges of the pre-Flood land masses, possibly in lagoons and/or in shallow waters, fringing the coast of areas like the proposed 'dinosaur peninsula' (figure 3). The lycopod trees may have been simply torn loose and deposited *en masse* within the lower sedimentary strata of the Absaroka Megasequence as the floodwaters continued to rise…. All geologic data support a 'grounded' lycopod forest that was growing attached to the pre-Flood land surface. (p. 55).

Furthermore, Clarey and Tomkins (2016) consider tree-lycopsid rhizomorphs and trunks to have been filled with aerenchyma (parenchyma with limited wall-to-wall contact and cell-sized or larger air spaces between cells, thus a spongy tissue) not hollow air chambers and, therefore, not candidates for a floating lifestyle since the cells, though widely spaced allowing air flow, would still have been filled with water. They describe it:

> Another line of reasoning put forth in support of the floating-forest hypothesis is that the arborescent lycopod trees were allegedly hollow in both their main aerial trunks and in their stigmarian roots—a contention based primarily on superficial speculation and not soundly supported by the scientific literature (Clarey and Tomkins 2016, p. 118).

Therefore, given the pervasive acceptance of the autochthonous origin of coal in coastal mires or swamps among conventional scientists and the objections within the creationist community, we need to examine the biology of the dominant coal plants in the post-1940 conventional paleobotanical literature to provide sound support by the scientific literature for a floating lifestyle. We survey the paleobotanical literature in a separate paper (Sanders and Austin, 2018).

CONCLUSION

Three hundred years ago, French botanist Antoine de Jussieu (1718) made important observations leading to the series of critical geological studies on the origin of Carboniferous coal that continue to the present. Autochthonous and allochthonous explanations in the early Nineteenth Century showed how scientific methodology becomes involved in coal interpretation. Autochthonous modelers used the paleobotany-strata-petrology-environment method, while allochthonous modelers used the petrology-strata-paleobotany-environment method. The two methodologies are best displayed at the end of the Nineteenth Century in the consensus autochthonists versus the French School allochthonists. Are coals terrestrial or subaqueous? Three explanations have been offered for the origin of coal: (1) peat swamp model, (2) drift model, and (3) floating mat model. Many paleobotany questions about lycopods and tree ferns had not been solved at the end of the Nineteenth Century, but the "floating mat model" offered a very robust path to direct research. Unfortunately, at the beginning of the Twentieth Century when the uniformitarian paradigm prevailed, the floating mat model was intentionally suppressed. We are here telling the three-hundred-year story for the first time.

Although a strong sedimentary case can be made for the floating mat model for prominent Carboniferous coal beds, many geologists resist this way of thinking because (1) the scale of mat sedimentation is colossal and associated with marine flooding, and (2) the coal-forming plants are supposed to have been adapted uniquely to the terrestrial swamp environment. This second supposition is now challenged by an improved paleoecology of tree lycopsids and the dominant coal-forest tree-fern *Psaronius* (Sanders and Austin, 2018).

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