STUDIES OF AMERICAN COAL BALLS.

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ABSTRACT. A large Upper Pennsylvanian flora has been found in the coal balls in the Des Moines rocks of Iowa, Missouri and Kansas. These petrifactions contain more than sixty species, most of which occur also in Indiana, Illinois and Kentucky, and in western Europe. The flora is correlated with the Westphalian C—D=Allegheny. The predominant plant groups are: Cordaitales, Pteridosperms and Ferns, with the Calamites, Lepidodendrids and Sphenophylls forming minor elements.

THE discovery of coal balls in America twenty years ago opened a new field of paleobotanical research in this country. The calcareous dolomitic nodules which occur in coal seams interbedded with shales and marine limestones were known in western Europe since the middle of the nineteenth century. Because of their detrimental effect in mining operations they attracted early attention, but it was the plant anatomist who first investigated and made known a large number of Carboniferous plants which were preserved in them. For nearly a century these petrifactions have yielded many specimens, giving detailed information concerning the histology of a variety of Paleozoic plants. The late A. C. Noé first collected American coal balls in southern Illinois and adjacent Kentucky. Subsequently they were reported in Indiana. All of these occurrences are in the Upper Pennsylvanian and are thus appreciably younger than the coal balls from England (39), Holland (20), Belgium (23), and Germany (14). Several years ago I began an investigation of coal balls from four localities in the state of Iowa, all of these referable to a stage in the Pennsylvanian equivalent to that of the Illinois coal ball flora. Since 1937 we have acquired large numbers of specimens from more than a dozen localities in Iowa and Kansas and a few from northwestern Missouri. These are of especial interest because they not only show a striking affinity with the well known coal ball plants of western Europe, but also exhibit many new forms which give a characteristic appearance to this American Pennsylvanian Flora.

Noé commenced his work about 1920 and encouraged many of his students to take part in the investigation of the abundant material from Illinois. Numerous papers were published by

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his active group, culminating with the critical work of Reed, Schopf and of the late Roy Graham, who unfortunately was killed in a rock fall a few months ago at the period of his greatest productivity.

Various technical methods have been adapted in our laboratory which give both the external and internal detail of the various species of plants represented. One of the greatest limitations in the study of petrifactions is the infrequence of related impressions, with the inevitable result that one cannot, in most cases, identify a structurally known species with an already described species based upon impressions. It was found that no great loss of material attended the splitting of coal balls with a heavy sledge hammer, that certain planes of weakness made possible the parting of specimens along the impressions, and thus for more than one-half of our species we now know the external form as well as the internal anatomy. This simple departure from established procedure has made possible a closer comparison with known floras of the American Carboniferous than otherwise would have been possible. The great bulk of material has been sectioned by means of sawn slices and cellulose nitrate peels. Thin sections have been ground so that various controls are available for comparison. The grinding method is slow and costly and in order to make thousands of preparations, a simpler, and at times somewhat less accurate, method had to be adopted. More than 40,000 mounted peels have been investigated and all of the described species have been identified and are available for distribution. Several new forms have already been proposed. In addition to these two methods, we have used complete maceration in order to recover spores, pollens and other tissues which can be used for a comparative study of the coal balls with the coals in which they occur. So far as I am aware, such a correlation has not hitherto been attempted. However, several years of effort must be expended before this aspect of our investigation will be deserving of publication.

OCCURRENCE.

Most of the coal balls reported in this paper occur in the upper half of the Des Moines Series of the tri-state region: Iowa, eastern Kansas and northwestern Missouri. They occur locally in coals which have been given restricted local names and numbers, partly in keeping with commercial practice. It is nearly impossible at the present time to identify any one coal with those from more distant localities, and hence until elaborate field observations have been made no detailed correlations are justifiable. All of the owners and operators have placed at my disposal log records, well records, and geological data, but I have not included the information in this summary. The generalization rather than detail is the important unit of a working hypothesis. These coals are to be compared with the Westphalian C in northwestern Europe and would fall within the Allegheny of the Appalachian region. It must be recognized, however, that the term Allegheny is of very limited implication if it is used in its strict sense (5). Those portions of the Pennsylvanian which are of post-Pottsville age are of much greater extent in the mid-continent region than in the northern Appalachian region. Some of the collections, particularly in Iowa, have been assumed to be near the Mississippian. This is an unfortunate error which overlooks the well known fact that the Des Moines rests unconformably upon older formations (25). The outline map (see Fig. 1 on the following page) shows the localities in Iowa at which coal balls have been found and at which specimens have been collected and studied.

Although the enumerations of species found at the various mines are strikingly similar, the association of species, especially in relation to dominant and satellic forms, bears contrast. The general nature of each of the local floral associations is indicated briefly in the following paragraphs.

SHULER MINE.

The most extensive series of coal balls was collected during 1937, 1938 and 1939 at the Shuler Mine near Waukee, west of the city of Des Moines, Dallas County, Iowa. More than 4,000 coal balls from these workings have been obtained and approximately one-half of them have been sawn and prepared for study. The number of species in this flora is slightly in excess of 60, of which 35 have been described. The remainder are of unique types which remain to be published, or of sporangia and seeds which are particularly difficult to interpret. It is my intention to leave these last two groups of species until the end of my investigations. I have elsewhere published (6) a general summary of the species present in the Shuler Mine and

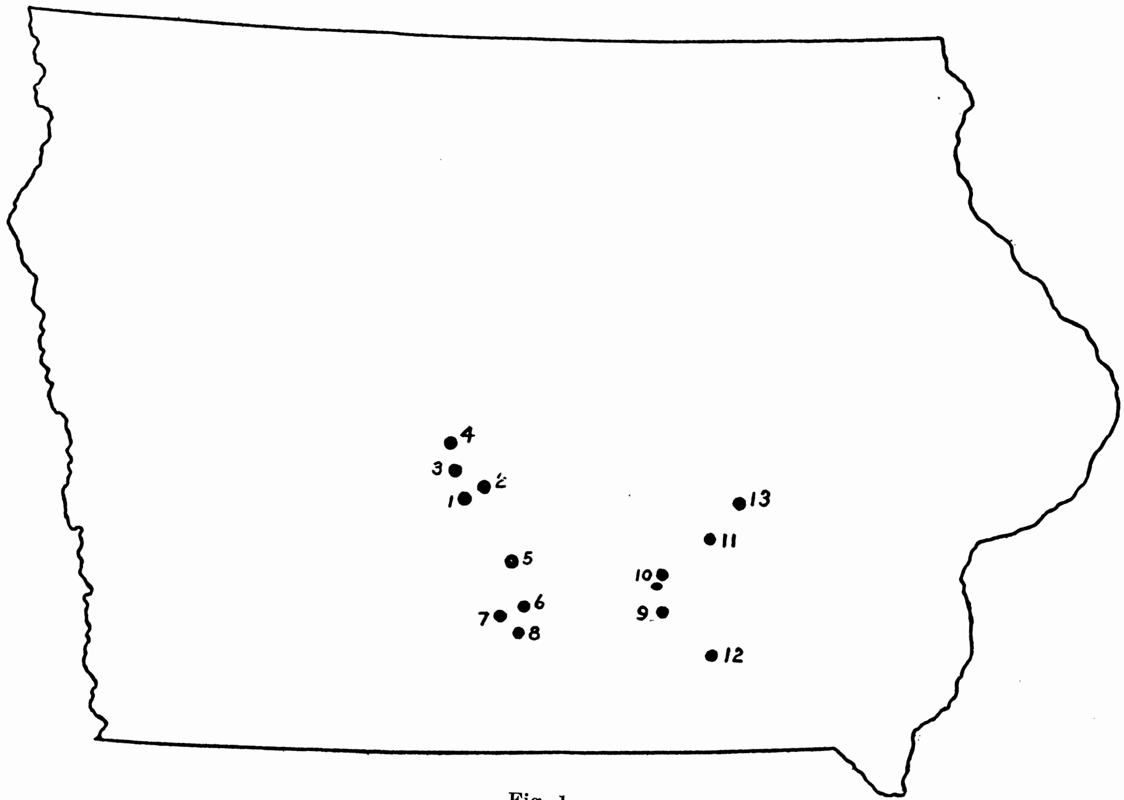

Fig. 1.

wish to add at this time only a general statement of the relative abundance of the characteristic forms present. *Cordaites* and all of its detached parts comprise the great bulk of the flora. Many thousands of fragments belonging, at most, to only two or three species are dominant. The wood type *Mesoxylon poroxyloides*, *Cordaianthus shuleri* (both male and female cones) and isolated seeds occur in great profusion. The seed ferns which comprise the next most abundant group are represented by various species of *Medullosa*, *Lyginopteris* and fern-like foliage. True ferns, although not as abundant as the cordaites and pteridosperms, are present in considerable variety. No less than 20 or 25 nominal species are present. Some of the most striking elements of the association are beautifully preserved fern stems with elaborate stellar construction. The lepidodendrids and their allies are present but are represented by only eight or ten species, and the number of individuals is exceedingly small, with the sole exception of the seeds called *Lepidocarpon glabrum.* These happen to be fairly abundant, approximately 400 specimens having been recognized. *Calamites* and *Sphenophyllum* are also among the more scarce elements, but they demonstrate at once how typical this Carboniferous flora really is.

URBANDALE MINE.

This mine, located in Walnut Township in Polk County, is only a few miles to the east of the Shuler Mine, but it is not certain whether the coal which is being worked at this locality is identical and continuous with the developed coal of the Shuler Mine. Local opinion holds that the two are distinct. The number of Urbandale coal balls which we have acquired is now great, but a ton of them arrived only a few months ago and these have not been subjected to investigation. Approximately 600 coal balls have been cut and examined. Not a single species which occurs at Urbandale does not occur also at the Shuler

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Figure 1. Outline of map of Iowa indicating localities at which coal balls have been collected. Number refers to key of names.

1. Shuler Mine.
2. Urbandale Mine.
3. Norwood Mine, No. 8.
4. Boone.
5. Melcher.
6. Williamson Mine, No. 3.
7. Williamson Mine, No. 4.
8. Williamson Mine, No. 5.
9. Hiteman.
10. Lovilia.
11. Oskaloosa.
12. Tillotson Mine.
13. What Cheer.

Mine. The preservation of the two series is not quite comparable, the Urbandale balls having a higher pyrite content and a lesser carbon content, although there are many balls of very inferior nature at both localities. The abundance of the different species and groups of plants holds to the same proportion as at the Shuler Mine, so that these species need not be enumerated again, but merely recorded in the chart which follows below.

TABLE 1.

Species of Coal Ball Plants From Iowa.

	Shuler	Urbandale	Williamson 3	Williamson 4	Williamson 5	Tillotson
Lepidodendron selaginoides	×	×	×			×
Lepidocarpon lomaxi	×	×	×			×
Lepidocarpon glabrum	×	×	×	×	×	×
Lepidodendron megaspores	×	×	×		×	×
Stigmaria (rootlets)	×	×	×	×	×	×
Calamites communis	×	×			×	×
Sphenophyllum plurifoliatum	×	×	×	×	×	×
Etapteris scotti	×	×	×			×
Ankyropteris grayi	×	×				
Anachoropteris involuta	×	×				
Psaronius sp.	×	×	×		×	×
Botryopteris americana	×	×	×	×	×	×
Botryopteris globosa	×	×				
Medullosa noéi	×	×	×	×	×	×
Mesoxylon poroxyloides	×	×	×	×	×	×
Cordaites crassum	×	×			×	×
Cordaites felicis	×	×	×	×	×	×
Cordaianthus shuleri	×	×	×	×	×	×
Cordaicarpus spinatus	×	×	×	×	×	×
Cordaicarpus sp.	×	×				
Lagenostoma ovoides	×	×	×			×
Pachytesta gigantea	×	×			×	×
Trigonocarpus parkinsoni	×		×			

TILLOTSON MINE.

The Tillotson Mine is situated to the southwest of Ottumwa in Wapello County.

This series of coal balls has been, for the most part, rather disappointing. The number of species is considerable but the degree of preservation is inferior to that of most of the other mines in Iowa. *Lepidodendron* is the most abundant form present, while *Sphenophyllum plurifoliatum* and *Botryopteris americana* are the next in frequence. *Medullosa noéi* and *Cordaianthus shuleri* are less abundant. Nothing of particular interest has been found in the Tillotson series in nearly 160 coal balls which have been sectioned, although the *Cordaites* are rather infrequent. The general association is very similar to that observed at Frontenac in Kansas and like that from Indiana and Illinois, rather than the association from the Shuler and Urbandale mines.

WILLIAMSON MINE NO. 3.

The three Williamson Mines (numbers 3, 4 and 5) are located near the town of Williamson in Lucas County. They are situated to the northeast of the village.

Cordaianthus shuleri, *Medullosa* roots, *Cordaicarpus spinatus* and a great variety of ferns at once correlate the flora with that of the Shuler Mine. In the first hundred coal balls approximately 30 species were recognized and agreement with the Shuler series is 100 per cent. *Cordaitean* leaves and *Mazocarpon* are quite abundant. The last named species is one of the rarer plants from the Iowa flora.

WILLIAMSON MINE NO. 5.

The plants of this mine were studied from a small series of balls of which 40 were cut and peeled and later a second series of 6 additional promising specimens were carefully sectioned. Only 14 species, all of them found in other localities, were encountered: *Cordaianthus*, *Mesoxylon*, *Medullosa* and various seeds comprising nearly the whole flora. The Williamson No. 5 coal balls have an unusually high pyrite content and the preservation is not as good as in the Williamson No. 3 series.

WILLIAMSON MINE NO. 4.

We have investigated the contents of approximately 50 coal balls from Williamson Mine No. 4. The number of species present is unusually small, there being recognized to date, only 9. All of them occur also at Williamson Mines, Nos. 3 and 5.

NORWOOD WHITE (HERROLD) MINE NO. 8.

I have obtained a few coal balls from this locality, which is located in Dallas County, 15 miles northwest of Des Moines, Iowa, on Highway No. 7, one mile north of the highway. There is almost no pyrite in these specimens, which is an unusual feature in the Iowa coal balls, but the plants present are very disappointing. Preservation is poor and the variety small. *Stigmaria* rootlets, *Lepidocarpon lomaxi* and *Psaronius* rootlets seem to be the only forms which have been recognized.

Small numbers of balls have been collected at several other localities, but the contents, so far as they have been studied, are too meager to deserve more than mention in this report. The names are given on the map.

A comparison of the species recognized in the more extensive local floras of Iowa coal balls is given in the accompanying tabulation.

The coal balls from Kansas which have been studied thus far were collected near the town of Frontenac. No attempt is made here to give an accurate stratigraphic account of the occurrence of this deposit, merely because the local terminology is not immediately correlative with that used in neighboring Missouri and Iowa. Twenty-two species have been observed in approximately a hundred coal balls. Some of the species are exceedingly scarce, being represented by single specimens. The most abundant plants are *Lepidodendron selaginoides*, *Sphenophyllum plurifoliatum*, *Lepidocarpon lomaxi*, *Botryopteris americana* and various fern sporangia. Of lesser importance but of relative abundance are the following forms: *Neuropteris*, *Medullosa noëi*, *Psaronius* and various seeds of the *Cordaicarpus* type. *Mesoxylon* and *Cordaianthus* are rather rare and they appear not only in small numbers but in relatively small fragments. In the first place it is a striking fact that nearly all of the species from the Frontenac deposits occur also at the Shuler Mine in Iowa. Only two species found in Kansas do not occur also at the Shuler Mine. On the other hand the relative abundance of the components of the flora are very different. Whereas at the Shuler Mine *Mesoxylon*, *Cordaianthus* and *Medullosa* comprise nearly 80 per cent of the specimens and *Lepidodendron* is exceedingly scarce, in Kansas the conditions are exactly reversed.

The coal adhering to the coal balls from Frontenac has been macerated by the usual methods and it was found that *Stigmaria* rootlets, fern spores, cuticles of leaves of *Cordaites*, and large megaspores of *Lepidodendron* occur in the coal. These do not differ in any particular from the components of the coal balls. This would seem to be consistent with the opinion that the coal ball has developed *in situ* and has not been transported into the coal bed after the ball was formed.

Most of the work that has been published relating to the occurrence of coal balls in America deals with the small field in southern Illinois and northern Kentucky. The number of species recorded is not large, although numerous lists of species have appeared. Two horizons are represented: the older is Allegheny (Harrisburg), the younger presumably Conemaugh (Calhoun). There is a remarkable degree of similarity between these balls and the various occurrences in Kansas and Iowa.

One of my students, W. S. Benninghoff, is at present investigating a small series of coal balls, approximately 150 in number, which he collected in Indiana, two miles north of the town of Petersburg, Pike County, at the horizon known as Upper Coal No. 5, according to the terminology of the Indiana Geological Survey. Dr. C. B. Reed of the United States Geological Survey kindly called our attention to this interesting locality. The number of species is very small and only a dozen species have been turned up to date. Benninghoff contributes the following enumeration to this report: *Lepidodendron selaginoides*, *Stigmaria* rootlets, *Cordaicarpus spinatus*, *Sphenophyllum plurifoliatum*, *Medullosa noéi*, *Calamites sp.*, *Psaronius* rootlets, and *Mesoxylon* species not yet determined. It is obvious that this flora is in no way different from that described from other American localities. The only point of interest which would render more exact the general complexion of this small flora is a note concerning the relative abundance of the components. *Lepidodendron* seems to be very abundant, while *Mesoxylon* and *Cordaicarpus* are more rare. Thus the closest similarity is with the deposit of Frontenac and not with the other floras from Illinois and Iowa. However, a similar assemblage has been found at the Tillotson Mine in Iowa where, despite large collections, the number of species is very meager and the flora is essentially a *Lepidodendron*, *Psaronius* and *Botryopteris* association.

In all of these floras there is a striking degree of similarity and it is noteworthy that in those localities where large numbers of specimens have been collected and subjected to investigation the greater numbers of species have been found. This is of course perfectly understandable and merely tends to indicate that rich floras occur also at other localities and await only further collecting in order that they may be known.

TABLE 2.

Tabulation of Described Species of American Coal Ball Floras.

	Iowa	Kansas	Indiana	Illinois	Western Europe	France Silicified Nodules
Bothrodendron mundum	×	×			×	
Lepidodendron selaginoides	×	×	×	×	×	
Lepidocarpon lomaxi	×	×	×	×	×	
Sigillaria approximata	×			×	?	
Miadesmia sp.	×				×	
Mazocarpon sp.	×			×	×(1)	
Stigmaria (rootlets)	×	×	×	×	×	
Calamites communis	×			×	×	
Calamostachys sp.	×			×	×(2)	
Macrostachya thompsonii	×			×(3)		
Sphenophyllum plurifoliatum	×	×	×	×	×	
Sphenophyllum dawsoni	×				×	
Stauropteris sp.	×		×		×	
Etapteris scotti	×			×		cf. E. laccattei
Ankyropteris grayi	×					
Anachoropteris involuta	×			×		×
Anachoropteris clavata	×			×		
Psaronius sp.	×	×	×	×	?	
Botryopteris americana	×	×	×	×	?	
Botryopteris hirsuta	×		×	×	×	
Botryopteris globosa	×					cf. B. forensis
"Botryopteris" fraiponti	×				×	
Medullosa noéi	×	×	×	×	cf. anglica	
Lyginopteris oldhamia?	×			?	×	
Mesoxylon poroxyloides	×				×	
Amyelon radicans	×			×	×	
Cordaites crassum	×					×
Cordaites felicis	×			?	×	
Cordaianthus shuleri	×	×				
Cordaicarpus spinatus	×	×	×	×		?
Cordaicarpus sp.	×			×	×	
Mitrospermum compressum	×				×	
Lagenostoma ovoides	×			×	×	
Physostoma sp.	×				?	
Pachytesta gigantea	×			×	×	
Trigonocarpus spp. (3)	×			×	×	

(1) cf. Mazocarpon shorense Benson.
(2) cf. Calamostachys oldhamia Will.
(3) Mazon Creek, Illinois—not coal ball.

In the accompanying chart comparison is made with the American coal balls and with their European equivalents. In the several columns on the left there are given the names of the American forms so far as they have been accurately determined. In the several columns to the right there are given the occurrences of the same species, or very closely related ones, in the several coal basins in northwestern Europe. It has been necessary to omit from this list a number of specimens representing new or difficult species which have not been fully described, owing to the fact that much, of course, remains to be done on them. Since it will be a matter of several years before some of the species can be adequately described, and since they will not modify the general correlations which are now possible, no harm can result from their omission. I have compiled the list of the Illinois forms from the publications of Noé, Graham and the other members of the University of Chicago group.

The question naturally arises, are all of these deposits homotaxial, i.e. to say, synchronous or contemporaneous? At least three criteria must be applied to each of the species before a full answer can be presented. First, what is the life span of a given species? It is well known, for instance, that many species are long lived and extend at times throughout several distinct geologic formations in the same locality. Thus the age of a species would endure many thousands of years. Certain existing species have an age exceeding several million years, having unbroken histories since Miocene time. A more warranted analogy can be made with the so-called "impression species" of the Pennsylvanian. Some species occur throughout the upper half of the Pennsylvanian—a time duration of considerable extent. Secondly, the specific identity of each species must be determined accurately. This is very difficult in the light of the insufficient description and illustration which, unfortunately, characterized so much of nineteenth century paleobotany. Only with the most critical revision will such work be possible. Thirdly, the range of variability of plant structures remains to be determined. Paleobotanists by necessity draw morphologic species very broadly. This might seem to be paradoxical, but it is a truism. In other words, there is no reason to doubt the general contemporaneity of all of these deposits; yet it is probable that the time-duration of the floras is of great length and that their chronologic range during the Pennsylvanian is of some magnitude. I doubt very much whether all of these floras could be more closely correlated on the basis of evidence at hand than to positions within the same series. We cannot choose between a temporal and ecological explanation for the *Lepidodendron* association at certain localities and a *Cordaites* at others.

Doubt has been expressed at the peculiar complexity of the floral list of plants found in Illinois coal balls compiled by Noé (26, 27, 28) on the ground that not only did he recognize the presence of a large number of lower Pennsylvanian forms, such as *Lyginopteris*, but also in the same beds there were other species which were believed to be allied with forms found in the Permian of western Europe. I held to this suspicion for a time, but now recognize that within certain limitations Noé's opinion was astute and shrewd. The Iowa coal ball flora differs little in specific content from that of the Illinois coal ball flora, and demonstrates, even more convincingly, how complex the association is. These floras are probably equivalent and correlative to the upper Allegheny of the Appalachian region. I do not believe any of the deposits can be of middle or late Conemaugh age, because none of the "impression species" observed in the coal balls is similar to typical Conemaugh plants.

This flora shows several relationships with the Stephanian floras of France, although it is much older. The species which Noé regarded as Permian are primarily Stephanian as now admitted by both French and German paleobotanists. This fact, together with the probability that species cannot be drawn too accurately on the basis of gross structure and the histology of the stems, makes it impossible to doubt the apparent coexistence of both earlier Pennsylvanian and later Pennsylvanian forms in the same flora. The association may be accepted as transitional in time and content. The presence of many species of the British coal ball flora in Illinois and Iowa is easy to demonstrate. The predominant members are primarily these so-called British types, most of which occur also in northwestern Germany. The most noteworthy are: *Lepidodendron selaginoides*, *Lepidocarpon lomaxi*, *Botryopteris hirsuta*, *Sphenophyllum plurifoliatum* and *Mesoxylon poroxyloides*.

Mention has been made concerning the impressions of various plants on the broken surfaces of many of the Shuler coal balls. The list of recognizable forms is significant:

Calamites cf. *suckowi* Artis
Neuropteris ovata Hoffm.
Neuropteris scheuchzeri Hoffm.
Neuropteris rarinervis Bunb.
Alethopteris serlii Brgt.
Pecopteris dentata Brgt.
Pecopteris miltoni Artis
Pecopteris arborescens Schloth.
Linopteris münsteri Eichw. (*L. gilkersonensis* D. W.)
Odontopteris sp. cf. *genuina* G' E.
Sphenopteris sp. cf. *neuropteroides* Boul.
Cordaites sp. (small leaves)

The histological structure of each of these is now known.

This small florule has a typical Westphalian appearance (40, 41, 42) but most of the species have extensive vertical distributions. *Neuropteris ovata* and *Neuropteris scheuchzeri* characterize the zone of Westphalian D and Upper C which, in the Appalachian province, embraces Allegheny and perhaps basal Conemaugh. *Neuropteris rarinervis* and *Pecopteris dentata* are more indicative of the older Westphalian C, although they are abundant in the basal portions of Westphalian D. *Alethopteris serlii* occurs in both Westphalian C and D, being somewhat more abundant in C. *Linopteris münsteri* is of Allegheny age (1), but it occurs also in the upper Pottsville (Westphalian C and top B). *Odontopteris genuina* is a characteristic species of the French Stephanian. Our specimen is too fragmentary to permit an unquestioned specific determination but the similarity is striking. *Sphenopteris neuropteroides* is a typical Westphalian D form. The conclusion to be drawn from the above association of impressions is that the flora is most probably of Allegheny = Wesphalian D age. This interpretation, which is consistent with all of the evidence at hand, differs from those previously published in two particulars:

(1) All of the coal ball floras thus far found in America are essentially homotaxial.

(2) Their geologic age (Allegheny = low Westphalian D) is somewhat older than previously but tentatively accepted.

Most of the work dealing with the British coal ball floras has been published by botanists and morphological paleobotanists. The geological considerations have never been adequately emphasized. In Germany and in Belgium and Holland the reverse has been true and the chief publications pertain to general stratigraphic relationships. The most recent and comprehensive contributions are those of Hirmer (14, 15), who summarized all of the work known concerning European coal balls up to 1935. In his paper he included a brief statement of the relationship of the Illinois coal ball flora. So far as I am aware, he had not seen much American material and the agreement in plant content which he emphasizes is somewhat misleading, because the points of difference have not been considered.

It is more than likely that most of the structurally preserved species will ultimately prove to be referable to already known species of Carboniferous impressions. I base this opinion chiefly on the fact that all of the common impression species found in American types are either identical with, or closely allied to, various European forms. It is possible that many of the genera based upon stems and petioles will remain in the literature as distinct and valid types, because it is impossible to recognize the different kinds of stems by external form alone. So little data of diagnostic value can be ascertained from such impressions that any identification would amount to little more than a careful guess. It is probable that a proper understanding of petrified plants found in intimate association will contribute materially to a general understanding of the impression floras, once we can be certain that identities have been correctly determined.

One of the most important problems related to coal deposition, coal ball formation and the accumulation of clastic sediments in cyclical sedimentation, is the nearness to the environment which supported the vegetation which is preserved in fossilized condition. The usual assumption which may or may not be intended, is that the beds are so close to the place of plant growth that for all intents and purposes we are dealing with an *in situ* deposit. Some workers will object to this dogmatic criticism, but it is true that all assumptions dealing with edaphic problems accept a "nearby habitat or environment hypothesis." In a flora which contains a great number of species it is most likely that the flora represents accumulations from many kinds of habitats and that deductions concerning environmental conditions are only true in a general and comprehensive sense. It can be argued that the general climatic environment and the availability of water will be essentially the same for an extensive area, but this too is an assumption. One of the very interesting and little understood problems of the Paleozoic are the so-called "pure stands" of one or two species. There are many Permian and Late Pennsylvanian localities in the American southwest where practically the entire plant content of a given bed is *Walchia*, an early conifer. Above the Mason coal (lower Conemaugh) in western Pennsylvania, time and again the only plant which can be found is *Neuropteris scheuchzeri*. Many well preserved "floras" contain only four or six species. It is a fundamental question whether we are justified in accepting any coal as being absolutely *in situ* although it is probable that there are most American Pennsylvanian coals that are essentially *in situ*, i.e. the plants have been transported (drifted) at most for only a few miles. These questions cannot be answered at this time, but they deserve a voice and required investigation, in order that we may evalue the concept of uniformitarianism which permeates all of geologic thought.

A final word must be said concerning the supposed Permian and Stephanian elements which were believed to be represented in the Illinois flora. A glance at the enumeration of species in the preceding chart will show that the number of identical species found in American coal balls and the French silicified nodules from the vicinity of Grand Croix is only five species (3, 33, 34). However, the number of other forms which have allied, although not identical species, is at least double the number. The whole aspect is typically Westphalian. I have made no attempt to break down the European occurrences in this paper as to whether they were derived from England, northern France, Holland, Belgium or Germany. The coal ball floras of western Europe are so similar, even though they are of somewhat varied age, that nothing would be gained by this. The closest agreement exists between Illinois and Iowa, which is more or less as would be expected. Most of the publications pertaining to the Illinois flora have been based on careful studies of a small number of coal balls or of a given group of species, with the result that much work which is known to the investigating group has not yet reached a stage of publication. It is probable that the Illinois coal ball flora will be fully as rich as that from Iowa.

NATURE OF THE PETRIFACTIONS.

It is somewhat surprising to observe that the degree of preservation of tissues observed in the coal balls despite the high pyrite content is remarkably good: cell walls are firm and not disintegrated, cell contents in many cases still exist; even the more delicate parenchymatous tissues of the body can be studied from good specimens, and spores are rarely collapsed. In many of the pollens globules of oil and other substances are present. A comparison of various thin sections prepared by the usual grinding method demonstrated that the crystals of calcite and pyrite ordinarily do not penetrate the cell walls except in rare cases when the pyrite is the damaging material. In many examples the calcite seems to have filled the cavities of cells without stretching or bursting them. Apparently the pyrite has formed from the locus of a cell wall and extended outwards away from the wall. This significant fact must be understood: the plant cells have not been replaced by mineral. The plant body which has undergone chemical alteration is still present, but the altered products of the original cell walls are not carbon, they are complex organic compounds.

This possibility has been pursued somewhat further, although the results are still in preliminary form. If a fragment of coal ball is macerated in hydrochloric acid of low concentration (four or five per cent), the mineral portion or matrix will be dissolved completely. Small pieces of *Mesoxylon* wood have been macerated by this method and the freed cells (tracheids and ray cells) were studied by optical and chemical means. In the acid bath the wood underwent disintegration gradually, and at the end of a half-hour treatment the sludge was gently centrifuged and washed with distilled water. After several washings and all salts and acids were removed, the sludge was transferred to glycerin. The residue may be kept in "semi-permanent" mounts. The cells, which compose the sludge, can be bleached with chlorine water acting for several minutes and then washing with distilled water. The individual cells are quite complete, showing the typical elongate or fusiform shape, except the smaller ray cells which are rectangular on any face. The tracheids have the hexagonal bordered pits which are characteristic of all cordaiteans. Needless to say, if any advanced degree of carbonization had taken place the cells would not have exhibited a tensile strength sufficiently great to permit handling. The dried cells ignite readily and burn completely.

Prof. I. W. Bailey suggested that it might be possible to ascertain the nature of the substances which composed the tracheids. A group of cells were placed in 50 per cent sulphuric acid. Since they dissolved quickly it may be assumed that no cellulose was present. Cellulose would be expected to withstand dissolution up to a concentration of 72 per cent sulphuric acid. A lignin component could not be recognized. Alternating treatments with four per cent sodium sulphite solution and chlorination (with chlorine water) did not appear to have produced any visible change in the macerated cells. The phloroglucinol color reaction was negative.

The only interpretation consistent with these observations is that both the cellulose and lignin portions of the cell mass have undergone chemical alteration, probably hydrolysis, but simpler, more or less allied, substances are still present. The wall substances are of great interest. Under polarized light, the tracheids show birefringence, which is not caused by the presence of any residual calcite. The experiments have been repeated to insure complete removal of calcite.

Although it must be admitted that attempts to gain an intimate knowledge of the chemical nature of the petrifaction process in these coal balls have not resulted in any considerable degree of success, it seems perfectly possible that with additional material in some quantity, a satisfactory investigation could be accomplished with microchemical methods.

Most paleontologists have assumed that the presence of pyrite in a fossil precludes the possibility of good preservation. It is obvious that not only is there a high pyrite content, but also that excellent preservation is to be expected, at least in the Iowa and Kansas coal balls. It is noteworthy that Arnold has published recently an interesting Devonian flora based upon pyrite nodules found in western New York.

During the early part of our project, chemical analyses were made of samples of several typical specimens in order to determine the various ingredients present. The specific gravity averages about 3.5 and a freshly broken surface is usually metallic. F. A. Gonyer of the Geological Museum of Harvard University reported the following results:

Sulphur	32.27
Iron	27.12
Iron oxide	.76
Calcium oxide	19.56
Carbon dioxide	14.87
Water (+)	1.47
Water (−)	00.00
Silica	.70
Soda	.17
Organic matter	3.10
	100.02

I have compared this content with that of typical English coal balls (6) and emphasize that no dolomite occurs in American coal balls. The organic component is unexpectedly high, being nearly twice that of the average British coal ball. It will be seen from the above tabulation that the iron pyrite (FeS_2) amounts to nearly 60 per cent of the total weight. The calcium carbonate amounts to more than 34 per cent, and thus these two mineral ingredients comprise almost 95 per cent of the total weight of the ball. In order that the chemical and optical determinations might be verified and the relationships between the several ingredients determined, a sample was submitted to Dr. C. S. Hurlbut, Jr., who studied prepared powdered material, a thin section and polished section. I quote the following portion from his report:

"*Minerals.* The only minerals found in any quantity were pyrite and calcite. From the polished section it is easily told that the iron sulphide is pyrite and not marcasite. From the thin section and the powder the calcium carbonate was identified as calcite and not aragonite.

"Several grams of material were ground to pass a 100 mesh screen, and were separated into a heavy and light portion by means of bromoform. This was done in an attempt to make quantitative the percentage of pyrite. Microscope examination of the heavy portion showed that considerable calcite was present clinging to the larger pyrite grains. Little or no pyrite was present in the lighter portion. The heavy portion was treated with hydrochloric acid to eliminate the calcite and the remaining pyrite weighed. According to this method pyrite makes up about 55 per cent of the coal ball by weight. If calcite makes up the remaining 45 per cent, the density was measured by two separate methods and found to be about 3.3. This means that there is a considerable percentage of voids or of material of lesser density than the calcite.

"A few grains of quartz and plagioclase feldspar were seen in the powdered material, but their total quantity is negligible.

"*Mineral relations.* From the evidence presented by sections studied, one cannot unequivocally say which mineral was earlier, the pyrite or the calcite. The evidence does, however, point to the fact that most of the calcite was earlier and is being replaced by the pyrite. There are two generations of calcite, one that appears to be early and one that is quite definitely later than the pyrite. The early calcite is fibrous and radiates from scattered centers. To a degree its crystallization has been controlled by the cellular structure of the coal ball. The cell boundaries are usually the terminating places of the individual calcite units, but before terminating a single crystal may extend across many cells. In one place it was observed that each cell was made up of a single calcite unit quite independent of its neighbors. The second generation of calcite is found in veins that cut the ball without regard in the least to cell structure.

"The pyrite appears to have replaced the calcite in several places observed on the thin section. In places it may pick out a single cell to replace, and elsewhere it forms a large mass leaving no trace of the earlier organic structure."

CONCLUSION.

There are many problems which are directly or indirectly related to the presence of coal balls in American coal basins. It is well known, for instance, that coal balls occur only in those localities where marine limestones appear also in the sedimentation cycle. The very nature of petrifaction and the origin of the coal balls are still matters for investigation. It is perfectly clear that the simple explanation of mineral replacement and cellular destruction is not supported by observable facts, at least in many kinds of petrifaction. The recovery of plant products such as oils, waxes, resinoid bodies and cuticles suggests a far more complex problem of preservation. The general question of correlation is the most simple of elucidation. Critical comparison and identification of the various species make possible reliable conclusions. The histology and general phylogenetic position of each species is a matter for prolonged investigation but in itself is a simple procedure. It is to be hoped that this general summary of American coal balls will encourage many persons to visit these and additional localities, to collect material abundantly and to make known this important aspect of the Carboniferous flora which seems to be more rich and varied than that known in any other part of the world.

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