Occurrence and Significance of Marine Animal Remains in American Coal Balls

GEOLOGICAL SURVEY PROFESSIONAL PAPER 354-I

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SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 354-I

A description of intermixtures of marine animals and land plants occurring in coal balls in Illinois, Iowa, Kansas, and Oklahoma

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C. - Price 50 cents (paper cover)

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By Sergius H. Mamay and Ellis L. Yochelson

ABSTRACT

Coal balls are mineralized nodular masses found within some coal seams. Although coal balls have been known for over 100 years, only botanical contents have been previously reported in detail. In this paper, occurrences of marine animal fossils associated with plant fossils in coal balls are described.

Three types of coal balls are here recognized: (a) normal coal balls, containing only plants; (b) mixed coal balls, containing both plants and marine animals; and (c) faunal coal balls, containing only animals. Mixed coal balls are homogeneous, if the plant and animal remains are mixed throughout the matrix, or heterogeneous, if the marine fraction is clearly segregated from the normal fraction.

Homogeneous-mixed coal balls were found near McAlester, Okla., near Oskaloosa, Iowa, and in parts of the southeastern Kansas coal fields. Heterogeneous-mixed coal balls were found near Berryville, Ill., and faunal coal balls were found at two localities in Kansas.

Coal balls are particularly common near West Mineral, Kans. They are abundant in the Fleming coal, of Des Moines age, and also occur in the underlying Mineral coal. Observations of mining waste suggest that mixed coal balls constitute 1 to 2 percent of the coal balls recovered, although none were found in place. There may be some positive correlation between abundance of coal balls and elevations or "highs" in the Fleming coal.

Semiquantitative spectroscopic analyses and rapid chemical analyses of selected coal balls are included in this report. These contain the most comprehensive data on the chemical composition of coal balls yet published.

Other samples were dissolved in formic acid; the residues are described. Uncompressed spores were recovered from many of the samples, along with diverse animal remains. Selected specimens of spores and animals are figured, and identifiable forms are tabulated.

The fossils are replaced by a variety of minerals, occasionally within the same coal ball. Spore fillings from a single coal ball may be pyritic or calcareous. Gastropods may be calcareous, pyritic, or baritic in the same sample. Pelecypods recovered are pyritic or baritic. Some echinoderm columnals, cephalopods, and brachiopods are pyritized, and others are calcareous.

The presence of marine animals within coal balls is evidence of transportation of material from a marine environment to a nonmarine environment. Though all coal balls have heretofore been considered concretionary in origin, mixed and faunal coal balls are, at least in part, of clastic origin. The swirled texture of some homogeneous-mixed coal balls is further evidence of transport.

It is suggested that heterogeneous-mixed coal balls were formed when mud rollers containing animal remains were brought into the coal swamp by temporary marine inundation and were secondarily surrounded by normal coal ball material. Some homogeneous-mixed coal balls may represent discrete lumps of transported fossiliferous mud. The animal content of still others may have been introduced into the coal swamp in a mud slurry. These temporary marine inundations may have provided a source of calcium carbonate for the formation of some normal coal balls.

INTRODUCTION

In a previous publication (Mamay and Yochelson, 1953) we briefly reported the occurrence of marine fossils associated with land plants in coal balls of Pennsylvanian age. Subsequent field observations and accummulation of additional material have made possible a more detailed report.

Although the occurrence of coal balls has been known for more than a century and although they have been noted in the coal fields of various European countries and of the United States and Great Britain, we are not aware of any authenticated reports, earlier than 1953, of faunal inclusions within coal balls.

Darrah (1939, p. 135) stated that "many of the Belgian and English coal balls contain fossil cephalopods," but he presented no further information. Coal ball deposits in England and Belgium are overlain by marine beds containing abundant fossiliferous nodules, in which goniatites are the predominating fossil; Stopes and Watson (1908) and Leclercq (1952) discussed in detail this relation of British and of Belgian coal ball deposits, respectively. Since extensive research has been done on both British and Belgian coal balls but no mention has been made of animals within the nodules, there is a possibility that Darrah neglected to distinguish between roof-shale nodules and true coal balls.

Douville (1905), who discussed briefly the content of a few nodules from the coal fields of Yorkshire, England, recognized two types of coal balls, one containing only plant debris, the other containing sparse woody fragments among numerous marine shells. The second type were illustrated (Douville, 1905, pl. 6) as "Coal Balls du Yorkshire," but it is apparent that these specimens are actually roof nodules, distinct from the coal seam itself.

It may be that animal remains simply do not occur in coal balls of Europe or England. Alternative reasons may be the facts that the primary interests of most previous investigators were botanical and that most British studies were based on specimens obtained from professional collectors and were not seen in the field by the paleobotanists. The material on which the present report is based is unusual in that it contains not only the plant remains ordinarily associated with coal balls, but diverse assemblages of marine animal fossils as well. Because of its significance for the origin of coal balls, this material is described in detail.

PREVIOUS WORK

Although earlier workers, particularly W. C. Williamson, wrote many papers on the plant content of coal balls, it was not until 1908 that the geological aspects of coal balls were extensively discussed in the classical publication by Stopes and Watson (1908). Their paper reviewed all the pertinent information available at the time, and included several chemical analyses of coal balls. Stopes and Watson concluded that coal balls were formed in place, as a product of percolating marine waters.

Since the time of Stopes' and Watson's publication little has been written on the occurrence and formation of coal balls, However, many publications have dealt with the anatomy and morphology of plants preserved within coal balls, and a number of significant botanical facts have been reported. The years 1935–60 have seen a rapid expansion of this field of paleobotany in the United States, but a considerable waning of interest in England and Europe, where most of the early work was done.

Studies of coal balls in the United States were summarized in detail through 1950 by Andrews (1951). This summary includes a sketch of the history of coal ball research in Europe, as well as a brief discussion of the chemical composition and geological occurrences of coal balls.

The study reported here was started in 1952, when Mamay made a large collection of coal balls in southeastern Kansas and southern Illinois. Previously, Mamay's interests were centered on morphological aspects of the plant content of the coal balls, but his attention was drawn toward the geologic problems raised by the animal fossils found in a few of the coal balls. The presence of abundant gastropods among these faunas resulted in Yochelson's participation in the study, because of his interests in that group of animals. A preliminary account of this discovery was published (Mamay and Yochelson, 1953) because of the great rarity of known occurrences of marine animal remains within Paleozoic coal seams.

In May 1955, we studied field relations and collected more coal balls from previously known and from new localities. Interested paleobotanists contributed additional coal balls. Excellent examples of animal-containing coal balls were also found in previously unstudied coal balls collected near McAlester, Okla., by Charles B. Read. Laboratory studies were carried out during 1955 and 1956, and Mamay revisited some of the localities in 1957.

Two other short publications resulted from this study. Associated with the McAlester, Okla., coal balls were a number of calcareous fossiliferous nodules that presumably originated from the overburden of the Secor coal. The nodules contain a number of species of Foraminifera, some of which were epiphytic on a problematical alga, *Litostroma*. The Foraminifera were described and their depositional environment was discussed by Henbest (1958); Mamay (1959) described *Litostroma* in detail.

ACKNOWLEDGMENTS

Our colleagues Charles B. Read and James M. Schopf provided locality information and on several occasions helped us by their discussions of the coal balls. Emil Sandeen and Kenneth Moore of the Pittsburg and Midway Coal Co. and H. W. Compton of the Apex-Compton Coal Co. not only allowed access to their mining properties but provided valuable information regarding the occurrence of coal balls. Robert W. Baxter, University of Kansas, and Henry N. Andrews, Washington University, St. Louis, Mo., allowed us to examine their collections of coal balls and gave select specimens for study. Baxter also supplied geologic information and additional specimens from Monmouth, Kans., having visited that locality at our request in July 1957. We appreciate also the cooperation by other U.S. Geological Survey colleagues: Mona Frank and P. L. D. Elmore made the spectroscopic examinations and Paul W. Scott made the chemical analyses. Charles Milton identified several minerals, and S. O. Schlanger aided in interpretation of sedimentary

phenomena. Systematic identifications are to be credited as follows: Protozoa, Lloyd G. Henbest; Coelenterata and Bryozoa, Helen Duncan; Cephalopoda, Mackenzie Gordon, Jr.; Ostracoda, I. G. Sohn; Trilobita, A. R. Palmer; and conodonts, the late Wilbert H. Hass. David H. Dunkle of the U.S. National Museum examined the fish remains, and David Nicol, formerly of the U.S. National Museum, checked identification of the pelecypods. Robert M. Finks, Brooklyn College, identified sponge material, and R. M. Kosanke, Illinois State Geological Survey, checked spore identifications.

DEFINITION OF COAL BALLS

The results of this study show that coal balls are considerably more varied, texturally and biologically, than is ordinarily supposed. It is thus evident that some expansion of longstanding concepts is necessary, as well as some refinement and revision of definitions. Our emended definitions are presented here, before descriptions in detail of the various kinds of coal balls.

In classical usage (Stopes and Watson, 1908, p. 168) the term "coal balls" has been applied to nodular mineralized masses of petrified plant material that occur within coal seams. The balls are largely restricted to coals of Pennsylvanian or equivalent age,[1] and generally have been considered to be concretionary in origin. There are no known occurrences in anthracitic coals.

Coal balls are of various physical and chemical features. They may be calcareous, pyritic, dolomitic, sideritic, or even siliceous in composition. Within limits, coal balls with high proportions of calcium carbonate have the best preservation of cellular detail; as a general rule, high pyrite content results in poor preservation of the plant fossils. The balls may occur as small individuals no larger than a plum, or they may weigh as much as several hundred pounds and may form huge intergrown masses that displace the coal for areas of several square yards. The individual nodules may be spheroidal, approximately lenticular, or irregular in shape. At a few localities, particularly in England and Europe, spheroidal specimens are very abundant, but at others, flattened, roughly lenticular coal balls seem to predominate. Coal balls may occur anywhere between the upper and lower limits of a coal seam, but they are more common in the upper half. In many places they cause humps in the upper surface of the coal, where they are separated from the overlying rocks by only a thin veneer of coal. Their occurrence in a given coal seam may be either extremely sporadic or regular; many seams contain none at all.

Despite these varying factors, two primary features have been necessary for identification of a sedimentary rock as a coal ball, as heretofore understood: (a) that it contain histologically investigable fossil plant material, impregnated with and surrounded by a mineral matrix of nonvegetable origin, and (b) that it be indigenous to a coal seam.

Schopf (Whitehead and others, 1952, p. 290) reported an occurrence of coal ball limestone in a marine coquina above a coal seam. According to Schopf, this obviously formed within the precoal peat bed and was reworked into its present position; it thus is not in conflict with this definition.

This study shows that coal balls may vary as much in their enclosed organic remains as they do in any other measurable feature. Thus a realistic definition of coal balls should be expanded so that "inclusion of histologically investigable plant material" is replaced by "inclusion of fossil animal material, histologically investigable fossil plant material, or both, in varying proportions" as one of the two primary requisites for identification of a rock as a coal ball, its inclusion within the limits of a coal seam remaining the other. The definition is further emended to include in its scope objects of either clastic or concretionary origin, their inclusion within the coal seam rather than source of component fossils being the important factor.

Carrying this concept to an extreme, it might be argued that any fossiliferous lens in coal is a coal ball, but this is fallacious logic. Coal balls are relatively small, discrete masses of nodular aspect, usually but not always wholly concretionary. They generally show a vertical distribution throughout the coal, rather than a lateral continuity such as characterizes a split, parting, or lens within a coal. The essential feature of the primarily clastic coal balls is the exotic nature of some of their fossil content, which is foreign to the immediate environment of coal deposition. In no sense are the clastic coal balls a normal part of the sedimentary cyclothem characteristic of Pennsylvanian sedimentation. We believe that their presence within a coal seam along with the more usual, concretionary type of plant-containing coal balls is attributable to unusual, probably catastrophic and transitory means of landward redeposition, such as might be effected by violent storm wave or tidal wave action.

It is emphasized that this broadened definition of coal balls is made only on the basis of specimens that can be shown, by virture of coal remnants on all or nearly all unfractured surfaces, to have originated within a coal seam. The various types of fossiliferous nodules that occur in the shaly or limy overburdens of

[1] Gothan (1911) reported masses of petrified plant material in German Tertiary brown coals, which he considered to be analogous to coal balls. The plants are preserved in siderite, however, and are not as well preserved as those in Carboniferous coal balls. Little more is known of this Tertiary occurrence.

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some coal seams are not regarded as coal balls because of their formation outside the coal seam. (See Stopes and Watson, 1908, p. 204–210, for discussion of goniatite-bearing nodules that occur in roof shales of some seams and occasionally contain well-preserved plant remains.)

The objects defined here as coal balls fall into three primary types, on the basis of biological content, and two subsidiary types, on the basis of textural features. The term "coal balls," unqualified, is used here for all these types. Although there is some intergradation in the relative proportions of plants to animals, for the sake of convenience coal balls may be classified as follows:

1. Normal coal balls: contain only plant fossils (pl. 27, fig. 1; pl. 28, fig. 2).
2. Mixed coal balls: contain both plant and animal fossils.
   (a) Homogeneous type: shows no distinguishable segregation of plant and animal fossils (pl. 27, figs. 2–4; pl. 28, fig. 3; pl. 29, figs. 1–3).
   (b) Heterogeneous type: shows distinct segregation of plant and animal fossils (pl. 30, figs. 1–3; pl. 31, fig. 1).
3. Faunal coal balls: contain exclusively zoological fossils (pl. 28, fig. 1; pl. 32, figs. 1–3).

Type 3 is very rare, and insofar as we know, has been found in significant quantities at only one locality. Type 2(a) (homogeneous-mixed) is by far the commonest type of animal-containing coal balls, while type 2(b) (heterogeneous-mixed) is, again, known to us from only one locality.

The following evidence supports this expanded concept of coal balls: In one coal ball (sample E–13, from Patik Mine, Iowa, pl. 31, fig. 4) animal remains are so rare as to be hardly noticeable on sawn surfaces, but acid solution produced a large number of small animal fossils, some of them unquestionably of marine origin. However, the plant debris is extremely well-preserved, and it is probable that casual inspection would lead to identification of the specimen as a normal coal ball.

It is possible to demonstrate a gradational series in which the proportion of animals to plants increases from the above-mentioned extreme in which animal remains are rare but present, to the point where plant remains are rare or even absent, as in some of the faunal coal balls. The faunal coal balls appear in the same seam with poorly preserved normal coal balls. There is no sharp line of demarcation between them and more intermediate specimens with higher proportions of plant fragments.

Comparison of normal coal balls from the Berryville, Ill., locality with the normal coal ball matrix surrounding the marine fraction of heterogeneous-mixed coal balls from the same locality indicates that the two are identical in physical composition, in texture, and in botanical content, as shown by study of peels and insoluble residues.

OCCURRENCES OF ANIMAL-CONTAINING COAL BALLS

Mixed coal balls were collected from localities in four States in the eastern interior and midcontinent coal basins: Illinois, Kansas, Oklahoma and Iowa. The Oklahoma deposit is no longer accessible. The Illinois specimens were found at a spot locality. The Kansas material, however, originates from an economically important mining area in the southeastern part of that State. This area has produced abundant coal balls from three different coal seams and has been the geographic source of much of the geologic information on the occurrence of mixed coal balls. The Iowa material consists of one coal ball from the Patik mine near Oskaloosa, presented to us by R. W. Baxter, University of Kansas.

Schopf (1941) published a chart showing important coal-ball stratigraphic levels in the United States and their correlation with European occurrences. Since this chart was prepared, only slight modifications in the correlations have been made (Moore and others, 1944; Wanless, 1956), so the chart is not repeated here. Geographic distribution of the mixed coal balls is shown in figure 42.

McALESTER, OKLA.

A small collection of coal balls from the Secor coal near McAlester, Okla., was made by C. B. Read in 1939. Only a few of the specimens were sectioned before 1953, and all those were of the normal type. Sectioning of the remainder showed that some were of the mixed type.

The collection was made at a small abandoned slope mine on the property of Mr. Joseph Lemont near the abandoned railroad station of Chambers, about 4 miles south-southeast of McAlester. The mine site is approximately at the common corners of secs. 26, 27, 34, and 35, T. 5 N., R. 14 E., Pittsburg County. This locality (USGS paleobotanical loc. 8764) was revisited by us in 1955, but only a few badly weathered loose coal balls were found. These all were of the normal type and no information was available regarding their original placement in the coal seam. The slag heap contained fragments of an impure bioclastic limestone. Similar limestone that was collected by Read corroborates a statement by Mr. Lemont that at the mining site the coal seam was overlain by a thin fossiliferous limestone.

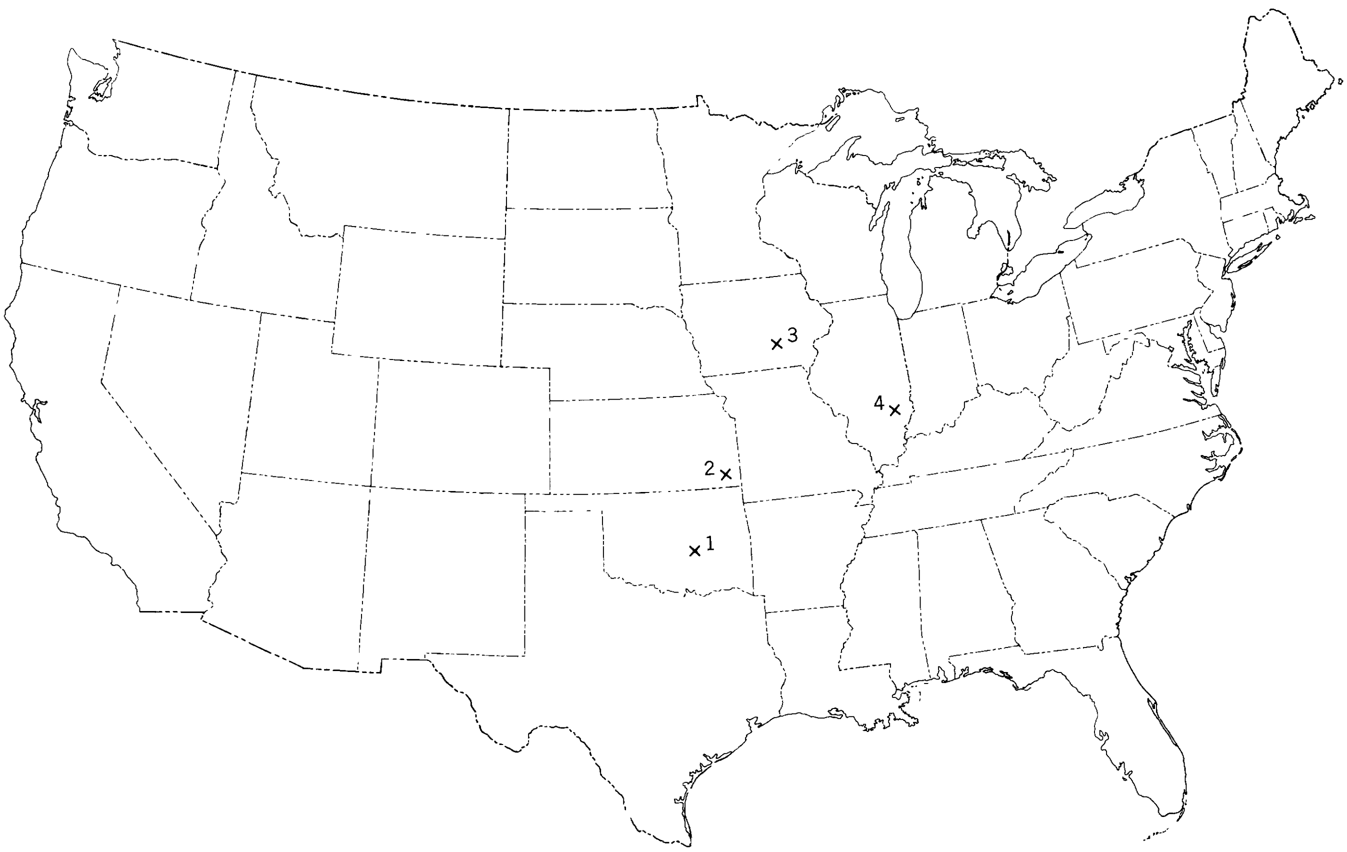

FIGURE 42. Geographic occurrences of mixed coal balls in the United States: 1, McAlester, Okla.; 2, southeastern Kansas; 3, Oskaloosa, Iowa; 4, Berryville, Ill.

Waste heaps of two other small abandoned mines in the nearby vicinity of the Lemont property (SW¼SW¼SW¼ sec. 26 and NE¼NE¼NE¼ sec. 34) were also searched for coal balls but none were found; only a few large scaphopods and poorly preserved peleypods were found.

Along the highway between Hartshorn and McAlester, we examined several large abandoned strip pits in the McAlester coal in the McAlester shale, 1,200-2,500 feet below the base of the Boggy formation. A large abandoned strip pit where the Secor coal had been mined in the southern half of sec. 33, T. 5 N., R. 15 E., was also searched. None of these pits yielded coal balls.

The Secor coal is the oldest seam known by us to have produced mixed coal balls. According to Hendricks (1937), the Secor coal seam varies from 1 to 3 feet in thickness. It lies about 350 feet above the base of the Boggy formation in the Krebs group, of Des Moines age (Miser, 1954). Hendricks mentioned no fossiliferous limestone above the Secor coal; perhaps he did not observe it either because of its localized occurrence or because it is covered over large parts of the area.

BERRYVILLE, ILL.

The locality known in the literature as Berryville, Ill., was discovered by J. Marvin Weller in August 1936 (Schopf, 1956, written communication). It is on the farm of Ralph Brian, 6 miles south and 2 miles west of Sumner, Ill. (approximately SW¼NE¼NW¼ sec. 7, T. 2 N., R. 13 W., Lawrence County; USGS paleobotanical loc. 9190). Since its discovery, this deposit has become well known to students of coal ball floras of the United States and has provided them with an unusual quantity of excellently preserved plant fossils, many of which have been described. The deposit is of further interest as a source of heterogeneous-mixed coal balls.

The coal balls occur in a thin seam of coal, considered by Schopf (1941) and others to be the Calhoun coal, in the upper part of the McLeansboro group of Middle and Late Pennsylvanian age. The outcrop is limited, being exposed for a distance of less than 60 feet along the south bank and bed of a small intermittent stream. The streambank cuts into the side of a steep hill, and a thick alluvial overburden hampers efforts to excavate the coal balls. Intermittent flooding of the stream erodes coal balls from the outcrop, so that collections may be made from float in the nearly dry streambed.

Several dozen fresh coal balls were collected at Berryville. Many of these were taken from the outcrop and broken in the field but none proved to be of the mixed type. A few heterogeneous-mixed specimens were found in float along the streambed, but these give no indication of their original position within the coal seam. The locality was revisited in 1957 by Mamay, who excavated heterogeneous-mixed coal balls in place and found that they extend throughout the thickness of the coal seam.

The outcrop area is shown on plate 26, figure 3. Because this exposure represents one of the few localities known to us where coal balls may be observed in place, the hillside adjacent to the outcrop was trenched and a section measured. The trench is seen along the right side of the photograph. The section consists of the following lithologic units:

Measured section at Berryville, Ill.

	Feet
Alluvium.	
Sandstone, light-gray, fine-grained; weathers dark gray; bedded in ½-in. laminae near base; becomes more massive upward	1.5
Shale, dark-brown, micaceous, with abundant fragmentary plant compressions; locally subfissile; poorly exposed	6.1
Limestone, dark-gray; highly crinoidal in a single massive bed; weathers very dark gray below and yellow iron stained above	1.0
Coal, moderately hard, banded, with blocky fracture; coal balls rare in lower 3 in., but become more numerous upward; some cause bulges in the upper surface of the seam. Average thickness of unit	2.0
Underclay, light-gray, slickensided with blocky structure; slightly arenaceous with scattered plant compressions; upper surface slightly irregular. Base not exposed, but thickness of unit at least	2.0
Total thickness measured	12.6

Examination of the coal seam face revealed the following distribution of the coal balls:

1. The relative abundance of the coal balls varies considerably within short horizontal distances; one spot may contain many, another a few feet away may have none.
2. Coal balls occur throughout the thickness of the seam.
3. Coal balls may occur at the base of the seam with only a thin film of coal below, and may even indent the subjacent underclay. Commonly, however, they seem to increase in abundance toward the top of the seam.
4. The coal balls that occur at the top of the seam may produce a bulge that protrudes into the overlying limestone. In all places observed, however, they were separated from the limestone by at least a thin film of coal.
5. The coal balls may be discrete lumps separated from each other by several inches or more of coal, or they may occur in large irregular intergrown masses that largely displace the coal seam for several square feet and contain only thin, irregularly oriented coal partings. One such mass is shown in plate 26, figure 2. This block of coal ball material, weighing perhaps a ton, stands isolated in the streambed. It consists of many closely associated, irregularly shaped but discrete masses of coal ball material separated from each other by thin streaks of coal. Although the overburden is completely eroded away, the intact condition of the underlying coal suggests that this mass is in its original position. It consists almost exclusively of the roots and other debris of the marattiaceous fern genus *Psaronius*, a dominant form in the Berryville flora.

Although nothing unusual was noted in the measured section, a somewhat involved sequence occurs a few yards downstream from the trench exposure (to the left of the trench in pl. 26, fig. 3). There the limestone overburden of the coal seam thickens abruptly to form a conspicuous mass approximately 5 feet thick. The coal beneath this limestone mass is reduced to approximately half its maximum thickness (see pl. 26, fig. 1), presumably by channeling, and the depression is filled with a mixture of detrital coal and limestone chunks, which grade into solid limestone above. A sample of the limestone blocks within the channel filling, when dissolved in acid, proved to contain almost the same type of plant and animal remains as the mixed coal balls. The coal immediately below the channel filling contains abundant limestone blocks; a representative sample included:

1. A typical, well-preserved normal coal ball containing a large undistorted fragment of the fructification of *Botryopteris*.
2. Several chunks, approximately 1 inch thick, composed of numerous particles of coal ball-like material in a coal groundmass and interbedded locally with stringers of coal. The brown coal ball particles are subangular to subrounded; they are closely packed and some are even molded into one another. The latter characteristic indicates that the particles were plastic when the rock was formed. The particles contain mostly well-preserved, uncompressed spores (see analysis of residue of sample E–15) and bits of cuticle, but no animal remains. They may represent an agglomeration of detrital coal ball material that was

finely divided at the time of channeling of the coal seam. Illustrations are given on plate 31.

3. Two pieces of gray crinoidal limestone, surrounded by coal and locally intermixed with or separated from the surrounding coal by brown petrified plant debris.

SOUTHEASTERN KANSAS

The southeastern Kansas coal field contains some of the richest known occurrences of coal balls in the United States (Andrews and Mamay, 1952), and consequently has been the geographic source of much of the information presented here. Several coal ball localities were visited by us in Cherokee and Crawford Counties; most of these were found by a systematic investigation of the strip-mining operations mapped by Abernathy (1946, pl. 1). A more up-to-date map of stripping operations in the area, published privately in 1952 by the Apex-Compton Coal Co., Inc., was also helpful in this search.

WEST MINERAL, KANS.

Investigations of this area were concentrated at the site of stripping operations of the Pittsburg and Midway Coal Co., at their Mine No. 19, in W½ sec. 5, T. 33 S., R. 22 E., Cherokee County. This site was selected because of the extensive scope of mining operations, the abundance of coal balls, and the relative freshness of the material.

In spite of the many coal balls found at the Pittsburgh and Midway mine, observations of their field relations were restricted by the sporadic occurrences of the coal balls and by the nature of the mining methods. Large-scale stripping operations are used because of the thickness of the overburden (as much as 50 feet); consequently, the relations of the coal to the overburden are usually concealed by slump from the steep walls of the pits.

The overburden is removed in long swaths of several thousands of square yards by either a dragline or an electric shovel. The upper surface of the coal is thoroughly cleaned. Once exposed, the coal is broken by a pinning machine, loaded, and taken to the tipple for washing and sizing.[2]

The mining procedure, while highly efficient, does not result in a clean working face, so that position of the coal balls within the coal is usually badly disturbed. The procedure also limits observations of the relation of the coal to the underlying sedimentary rocks, for little of the latter are removed. Furthermore, loading usually takes place shortly after breaking of the coal, so that one would have to be present at about the time the coal balls are uncovered to observe them in place.

In addition to the limitations imposed by the mining methods, three other factors restricted our observations. First, at the time of our visit, even though a large area of coal was exposed, few coal balls were being uncovered. Second, in 1955, mining was limited to a single pit, and it was not possible to make comparative observations at fresh exposures over a broader area. Third, as usual in large strip-mining operations, abandoned pits that might have contained good exposures of the coal and overlying strata in their walls were either refilled with overburden or flooded to levels above the coal.

Our observations, however, have been supplemented by those of the miners and pit operators. Particularly valuable information was derived from discussions with Emil Sandeen, mine superintendent of the Pittsburg and Midway Coal Co., and with Kenneth Moore, mining engineer, Mine No. 19, and from mining records of that company, to which we were given access.

The mining method necessarily results in contamination of the coal by coal ball material and minor amounts of underclay. Where the balls occur abundantly, they are a major nuisance since they are imbedded in the coal and must be loaded and transported to the washing plant for removal. The waste removed from the coal in the washing process varies from day to day, partly because of the sporadic occurrence of coal balls, and sometimes may constitute more than 30 percent of the gross tonnage mined. Coal balls form a large part of this impurity.

Despite the inconvenience of commercially worthless coal balls, their occurrence is not a total loss to the mine operators. The coal balls, being of much higher specific gravity than the coal, are easily removed in the washing plant. The coal balls are hauled from the tipple and piled in a nearby vacant area until they are needed for road construction. Their hardness and durability make them an excellent ballast for access mine roads, a fact that has been fully exploited at the Pittsburg and Midway mines, where this supply of ballast is seemingly endless! Part of one such pile, which was perhaps 6 feet high over an area of half an acre, is shown in plate 26, figure 4—a heap of possibly several thousand tons of almost pure, structurally preserved fossil material. Another indication of the abundance of coal balls at the Pittsburg and Midway mines was observed in a newly constructed roadbed, some 1,800 feet long, 50 feet wide, and 2 to 3 feet deep. It was estimated that between one-quarter and one-half of the volume consists of coal balls.

[2] Mine operations at the Pittsburg and Midway Mine are more completely described in Coal Age (1954).

STRATIGRAPHIC RELATIONS OF THE COAL BALLS

Two closely associated coal seams are mined by the Pittsburg and Midway Coal Co. These are the Fleming and the Mineral seams, both of which occur near the bottom of the upper one-third of the Cherokee shale of Des Moines age. The Fleming is the uppermost coal. It ranges from 12 to 18 inches in thickness and lies from 8 to 20 feet above the Mineral coal, the thickness of which ranges from 18 to 24 inches. Both seams locally contain coal balls, but the balls are far more abundant and widespread geographically in the Fleming coal.

The Mineral coal, although of more sporadic occurrence than the Fleming, apparently more consistently maintains a single stratigraphic level. It may be present directly beneath the Fleming coal, or present in an area where the Fleming coal is absent. On the other hand, the Mineral coal may be absent from an area that does contain the Fleming coal.

In contrast to the flat-lying Mineral coal, the Fleming coal undulates, varying in vertical distance from the underlying seam. It may be flat and almost parallel to the Mineral coal for a large area, but locally it rises to form structural "highs" that extend as much as 12 feet above its general level. The "highs" may form domes as much as 100 feet across or ridges extending along the seam for 500 to 1,500 feet (K. E. Moore, 1957, oral communication). They are usually accompanied by a thinning of the coal at their crests. In areas where the Mineral coal is generally absent, an isolated patch of it may be present directly below a "high" in the Fleming coal.

The overburden of the Mineral seam also differs from that of the Fleming seam. The Fleming coal is overlain by a dark-gray to black fine-grained marine shale, rich in productoid brachiopods (Williams, 1938, p. 105). According to Mr. Moore, a limestone is not known to overlie this seam at the Mine No. 19 area. On the other hand, over broad areas, the Mineral coal is overlain by a hard massive impure fossiliferous limestone as much as 20 inches thick, which may change laterally in a short distance to a black shale similar to that above the Fleming coal. At one exposure at Mine No. 19, we observed a limestone 20 inches thick directly above the Mineral coal; 50 feet away, the coal was overlain by the fossiliferous shale. No coal balls were observed in the coal beneath the limestone.

The coal balls show the following relations to the two coal seams:

1. Relative abundance of coal balls, in general, shows considerable local variation. At Mine No. 19, the dragline pit (sec. 6, T. 33 S., R. 22 E.) had produced few coal balls, while the shovel pit, less than two miles away (SW¼ sec. 32, T. 32 S., R. 22 E.), had produced many.
2. Of the two seams, the Fleming coal produces by far the most coal balls.
3. A previous statement by us (1953) that coal balls occur only beneath a marine limestone caprock is erroneous, as is strikingly illustrated by the abundance of coal balls in the Fleming coal, where a marine limestone cap is absent. Furthermore, there seems to be no correlation between limestone and coal balls in the Mineral coal, where both are known to occur. Thus it appears that the one condition found consistently in occurrences of coal balls is that the productive seam is directly overlain by a marine bed, regardless of its lithology. Feliciano (1924, p. 233) cast some doubt on this but did not present detailed evidence.
4. The coal balls are generally more abundant in the upper half of the seam, but are known to occur throughout the thickness of the coal. In some places they replace almost the entire coal seam over areas of many square yards.
5. In the Fleming coal the abundance of coal balls seems to be related to the elevation of the coal seam. It was brought to our attention by Messrs. Sandeen and Moore, as well as by several of the Pittsburg and Midway Coal Co.'s shovel operators, that coal balls in the Fleming seam are usually concentrated at the "highs." Mr. Moore stated that tipple waste from "high" areas of the Fleming coal usually is greater than that from "low" areas in the seam, and may reach as much as 37 percent of the total volume, a large part of this waste consisting of coal balls. Sporadic occurrence of coal balls within a given coal seam has been reported previously (Cady, 1936, p. 158; Andrews, 1951, p. 433) and probably is characteristic of all deposits containing coal balls. Whether these other sporadic occurrences are also associated with "highs" in the coal remains to be determined.

These facts may have some bearing on the overall problem of coal ball formation, but they shed no light on the outcrop relations of mixed coal balls to normal ones. However, it is known that the two types do occur very close to each other. Along one of the mine access roads at the West Mineral, Kans., locality, there had been dumped, intact, a nest of coal balls approximately 3 feet square and 1 foot thick. The lower surface of the nest bore a 2- to 3-inch layer of coal; its upper surface bore a thin film of coal, superposed by an inch or so of black fossiliferous shale whose surface undulations marked the positions of the individual coal balls. Several of these were broken from the upper surface of the nest, and two proved to contain animal remains as well as moderately well preserved plant fragments; the rest of the collection consisted of normal coal balls with well-preserved plant structures. Thus it is at least known that mixed and normal coal balls may occur within 2 or 3 feet, horizontally, and a few inches, vertically, of each other.

Most of the mixed Kansas coal balls were collected from the roadbeds and ballast heaps of the Pittsburg and Midway Coal Co. Although it was not possible to observe the relation of mixed coal balls to normal coal balls or to arrive at any understanding of their real distribution, it was possible to gain some idea at least of their relative abundance. Mixed coal balls are no rarity at this particular locality, but, on the basis of examination of perhaps 4 or 5 miles of roadbed exposures and of the several large waste heaps in the area, we estimate that mixed coal balls constitute no more than 1 to 2 percent of all the coal balls spread about the Pittsburgh and Midway Coal Co.'s grounds.

The mixed coal balls show about the same range in size and shape as those of the normal specimens; several were more than 2 feet in greatest dimension and several hundred pounds in weight. Mixed coal balls were not concentrated at any one place, but were fairly evenly distributed among the normal coal balls and were found among the waste heaps and roadbeds of the abandoned Mine No. 15 as well as those of the then active Mine No. 19. This suggests an areal distribution approximating that of normal coal balls in the Fleming coal.

FRANKLIN, KANS.

Large heaps of coal balls were examined at the dumps of the Mackie-Clemens Mine No. 22 (SE¼ sec. 24, T. 28 S., R. 25 E., Crawford County) and Mine No. 23 (NW¼ sec. 21, T. 29 S., R. 25 E., Crawford County), east of Franklin, Kans. A few mixed specimens were found at the latter locality, an airline distance of nearly 30 miles from the Pittsburg and Midway Coal Co. pits.

Abernathy (1946) indicated the coal mined there to be the Mineral coal, but local inquiry indicated that the seam is considered by some miners to be the Fleming coal. On the basis of plant content and physical appearance, the coal balls examined there seem to be identical with those at West Mineral, where the Fleming coal yields most of the coal balls. Several other pits and dumps in this general area were examined without finding coal balls.

MONMOUTH, KANS.

The Bevier coal is exposed in an open-pit mine of the Apex-Compton Coal Co., in NW¼ sec. 12, T. 31 S., R. 22 E., Crawford County, near Monmouth, Kans. According to Abernathy (1946, p. 139) the Bevier coal lies above the Fleming and Mineral coals, about 100 feet below the top of the Cherokee shale. The roadbeds at the Monmouth pit, like those at the Pittsburg and Midway Coal Company, are composed largely of coal ball material, indicating regular and abundant occurrences of coal balls. But curiously enough, the coal balls themselves are predominately pyritized faunal coal balls or specimens containing negligible plant material. Only a few specimens of plant-bearing coal balls were found, and these are composed almost exclusively of fusinized wood fragments instead of the heterogeneous, calcified, and more or less well-preserved plant debris that occurs in normal coal balls. Thus it appears that the ratio of normal to animal-containing specimens at other deposits is almost reversed at the Apex-Compton mine, for the normal coal balls there constitute the smaller percentage, perhaps even a smaller percentage of the total than do the mixed coal balls at the Pittsburg and Midway pits.

The active pit was flooded at the time of our 1955 visit, and it was not possible to see the coal balls in place, but the following information regarding this curious occurrence was provided by H. W. Compton, owner of the mine:

1. A limestone has not been noted immediately above the coal in the Apex-Compton pits. The immediate overburden of the coal seam is a dark-gray slightly fissile shale containing productid brachipods, pectenoid pelecypods, and poorly preserved plant impressions near its contact with the coal. This shale ranges from 3 to 6 feet in thickness and is overlain by a 3- to 6-inch layer of medium dark-gray argilaceous unfossiliferous limestone; above the limestone is a light-gray nonfissile unfossiliferous shale. The overburden apparently lacks concretions and is generally very poor in fossils.
2. Coal balls are abundant and occur throughout the thickness of the seam. In some places they are so highly concentrated as to form sizable humps in the surface of the coal. As an exceptional example of the high proportion of the coal seam sometimes represented by coal ball material, Mr. Compton cited one particular pit, 80 feet wide and approximately one-half mile long, in which the coal was so heavily contaminated with coal balls that the pit was abandoned.
3. Although the surface of the coal seam shows some undulation, no correlation has been observed between the "highs" and coal ball occurrences, except where the elevations are actually caused by unusual concentrations of coal balls.

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In July 1957, Robert W. Baxter, University of Kansas, visited the Apex-Compton mine at our request, in order to study the field relation of the faunal coal balls under better conditions than those we found in 1955. Baxter's observations substantiate the above descriptions. He succeeded in observing, photographing, and collecting faunal coal balls in place at the working face of the coal seam, and forwarded us specimens and photographs for inclusion in this report. Part of the coal seam with two faunal coal balls in place is shown in plate 26, figure 5; sawn surfaces of these two specimens are shown in plate 32.

Baxter wrote us:

The seam exposed at the time of my visit averaged 16–18 inches thick. The swath of coal exposed while I was there was not over 60 yards long. In this area of mining, the Bevier seam is only 12–15 feet below the surface and the old pits are covered just about as fast as the coal is removed. Unfortunately, the area exposed was exceptionally clean of coal balls. The descriptions of Mr. Compton and three men who were working on the stripping shovel all tallied and agree that the coal balls tend to occur in pockets with a center of greatest density or abundance with gradually diminishing numbers towards the borders of the area. In the 16–18 inch seam they tend to occupy the entire seam from top to bottom in the pocket areas, the coal present being reduced to an embedding matrix. Just before we had arrived, the stripping shovel hit a small pocket occupying the entire thickness of the seam and had put the whole shovelful up on the far side of the pit. Samples of coal balls from this are being sent you. It was quite evident to me, from an examination of the almost intact shoveful, that the coal balls had filled the whole seam in that spot. There was a veneer of coal on all the coal ball material, but 90 percent of the shovelful was "rock."

Shortly after looking over the above, the stripping shovel exposed a large flat coal ball in place in the face of the seam with at least an inch of coal above it. A rounded, almost pure pyrite coal ball occurred slightly below it, deeper in the coal. Several pictures of the above exposure are enclosed and the two coal balls are being sent you.

Accordingly one can definitely say that these "coal balls" are abundant in the Bevier coal, usually in localized areas where they almost fill the seam, or in more isolated cases where they tend to occur in the upper part of the seam.

Regarding the underlying bed, Baxter wrote:

The coal seam lies on what I would consider a typical stigmarian underclay. Mr. Compton had the stripping shovel dig down into it for several feet. * * * Mr. Compton said the clay varied in thickness from up to 12 feet down to less than a foot thick, overlying a limestone layer. The depth of clay at the region of the picture was certainly over 3 feet.

Baxter observed that "none of the coal balls I saw, either in the pit or on the older dumps showed anything I could identify as plant material." He further stated:

While as indicated below, there is no doubt about the rather highly pyritized rock from this mine being coal ball material, in that it definitely occurs in the coal itself, it still seems quite different from most coal balls I am familiar with. For one thing, most of the rocks tend to occur as flat sheets, 2 to 3 inches thick. This makes it look suspiciously like similar fossiliferous rock from the overlying shale. However, there is no doubt that this occurs within the coal.[3] There is a smaller percentage of slightly rounded coal balls which almost always seem to be nearly pure pyrite.

In September 1957, Mamay revisited the Apex-Compton mine but made no significant additional observations, except that the overburden then exposed contained no fossiliferous rock with which the faunal coal balls could be compared.

Faunal coal balls were found at only one other locality, this being a small strip pit in the Bevier coal, owned by the Garrett Coal Co. and located in SE¼ sec. 34, T. 26 S., R. 25 E., Bourbon County, Kans. At this pit a few highly pyritized faunal coal balls were found in the uppermost 3 inches of the coal, which was about 18 inches thick. None were seen elsewhere in the seam, nor were any normal coal balls found.

PHYSICAL AND BIOLOGICAL FEATURES OF COAL BALLS

NORMAL COAL BALLS

The characteristics of normal coal balls were discussed thoroughly by Stopes and Watson (1908). A few comments are added here for the sake of completeness.

Normal coal balls show considerable range in the variety and preservation of their content, the quality of preservation being dependent on high percentages of calcium carbonate. Some contain little but roots or lycopodinean periderm, while others are rich in leaves and reproductive organs. A large number of samples from a given locality may give the investigator a reasonably sound basis for analysis of the local flora in terms of dominant and subdominant species.

Occasionally one finds a coal ball that consists of a single plant fragment. At the West Mineral locality, Mamay has found several well-preserved calcareous lycopod, medullosan, or psaronean stem fragments a foot or more long, surrounded by a film of coal and unaccompanied by other plant debris. The same locality yields large numbers of tiny "nucellar coal balls" (Roth, 1956), each of which consist of the internal parts of a single cordaitean seed.

Normal coal balls vary considerably in shape, some being nearly spherical. Specimens of this type seem to be most common in the English deposits but are rare in American deposits.

The contents of spheroidal coal balls usually show no layering or other textural peculiarities. Most com-

[3] Stopes and Watson reported apparently similarly shaped sheets of stone in the English coals; however, they considered the stone sheets, which they discussed only briefly and which contain only plant material, to be a "parallel formation to that of the normal coal balls" (Stopes and Watson, 1908, p. 176).

monly the plant fragments are uncompressed and otherwise undistorted.

Lenticular coal balls are common in American deposits. All degrees of lenticularity may be found, the most extreme having perhaps a ratio of less than one-quarter thickness to width. Some specimens are nearly circular in outline, relatively smooth-surfaced, and often slickensided. Coal balls of this type are common at the West Mineral, Kans., locality, some being nearly 2 feet in diameter. A West Mineral normal coal ball, irregular in shape but typical in composition, is shown diagrammatically in figure 43, and a lenticular specimen is illustrated on plate 28, figure 2.

Lenticularity is assumed to be the result of prelithification compaction, for lenticular specimens in place lie parallel to the bedding of the coal, with the laminae of the coal following the contours of the coal ball. This type of coal ball also presents the greatest consistency of relation of external shape to internal texture, for lenticular coal balls generally show distinct layering of the enclosed plant parts, the layering being almost parallel to the bedding of the coal. Stems with large or hollow pith cavities, such as the calamarians, are commonly flattened in lenticular coal balls. Furthermore, coal balls of this type commonly have a thin equatorial flange of well-preserved plant material that feathers out and disappears between laminae of the coal.

Aside from the spheroidal and the lenticular types of coal balls, there are no other regular or definable shapes that characterize these nodules. Coal balls have a variety of irregular shapes; angular external contours are, however, extremely rare. Specimens of irregular shape may show bedding or layering of their contents, but, on the other hand, commonly there is no definite arrangement of plant debris in the matrix.

Calcite-filled cracks, often penetrating nearly the entire width of a specimen, and concretionary mineralization patterns are common to all types of coal balls discussed thus far. Cracks may be abundant in a single specimen, and sometimes they fall into a roughly radial pattern that extends inward a variable distance from the periphery of the nodule. That such cracks often create a clean break in an otherwise undistorted and well-preserved plant axis suggests that they are probably compaction cracks, formed after initial mineralization had been completed.

HOMOGENEOUS-MIXED COAL BALLS

Homogeneous-mixed coal balls are mostly irregular in shape, although lenticular specimens have also been seen. Some homogeneous-mixed balls are slightly flattened, with layered alinement of the enclosed fossils, and in the lenticular specimens layering of fossils may be as clear as that often shown by plant debris in the lenticular normal coal balls. Calcite-filled cracks are common in homogeneous-mixed coal balls. A homogeneous-mixed coal ball is shown diagrammatically in figure 44 and others are illustrated on plates 27–29.

Animal and plant fossils may be randomly scattered through the entire coal ball, but in some the animals seem to be concentrated in poorly defined pockets. In samples of this sort the animal-containing pockets may be distinguished from the remainder of the coal ball by a slight difference in the color of the matrix, which

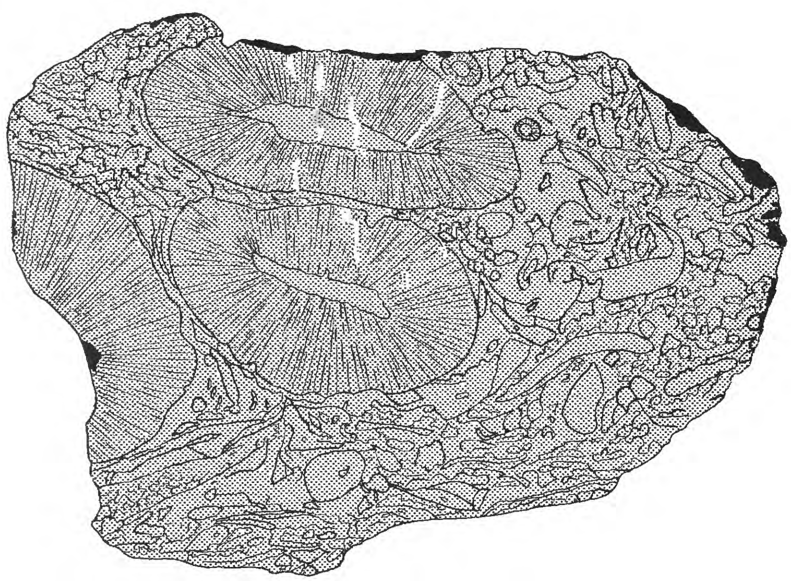

FIGURE 43.—Sketch of sawn surface of a normal coal ball from West Mineral, Kans., drawn from a peel preparation of specimen 9189–61E. Calcite-filled cracks are unstippled. Approximately 9/10 natural size.

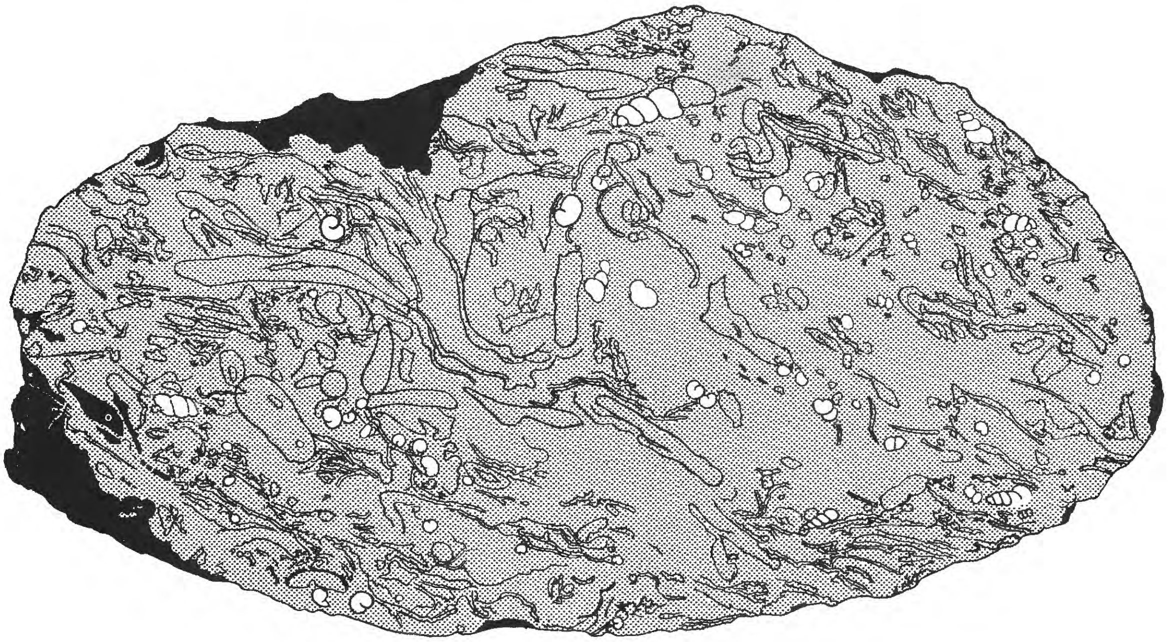

FIGURE 44.—Sketch of sawed surface of a homogeneous-mixed coal ball from West Mineral, Kans., drawn from a peel preparation of specimen 9189–120A. Unstippled areas represent animal remains. Natural size.

is not, however, sharply delineated from the surrounding matrix. Mixed coal balls with pockets of this type may also contain faunal and floral mixtures in other parts of the specimen.

Some homogeneous-mixed coal balls show a peculiar textural feature that is like the mixing together of two colors of cake batter and that we refer to as "swirled." This "swirling" consists of oriented lines of animal fossils. The lines nearly parallel each other, but are very irregular and bear no definite relation to the bedding plane of the coal where that feature can be inferred from the shape of the coal ball or adherent remnants of the surrounding coal. The swirl markings may also assume roughly concentric orientation, and may intergrade imperceptibly into coal ball matrix that shows no structure.

HETEROGENEOUS-MIXED COAL BALLS

Heterogeneous-mixed coal balls, which have been found only at Berryville, Ill., differ from all other types by showing a segregation of marine from nonmarine parts of the matrix; this segregation is illustrated in figure 45. Actually, this is not a simple segregation of plant from animals remains, for a certain amount of small resistant plant fragments (mostly well-preserved spores) is incorporated in the animal-containing matrix. However, this animal-containing matrix is surrounded by an area that contains only plant material and that in all aspects is typical of the matrix of a normal coal ball.

The marine masses, to which for want of a better term we refer as "cores," are of much interest, both structurally and biologically. They vary in form from elongate, more or less cylindrical rods that extend through the entire length of the coal ball, to irregularly shaped cores. The cylindroid type of marine core is illustrated in figure 45; others are shown on plates 30 and 31.

In the example shown in figure 45, as well as in several other examples, the coal ball is an elongate, slightly flattened specimen. The plant material shows perceptible flattening parallel to the long axis of the specimen. The marine core, which is slightly eccentric in position, extends through the whole length of the coal ball (approximately 16 inches) and is exposed at either end. It varies little in either its diameter (approximately 2½ inches) or its position relative to the center of the coal ball, and for the most part displays a sharp line of contact with the surrounding normal matrix. Here and there, however, a root or stem fragment or stringer of unrecognizable plant debris crosses the contact and extends a short distance into the core. In other specimens, though the contact between the core and the normal part of the coal ball is relatively clear, it is irregular and subangular in places.

The figured core is unusual in its deep embedment within the normal matrix and its nearly perfect cylindroid shape. Other cores are less regularly shaped and may constitute most of the coal ball. All cores, however, are surrounded by a layer of normal matrix with-

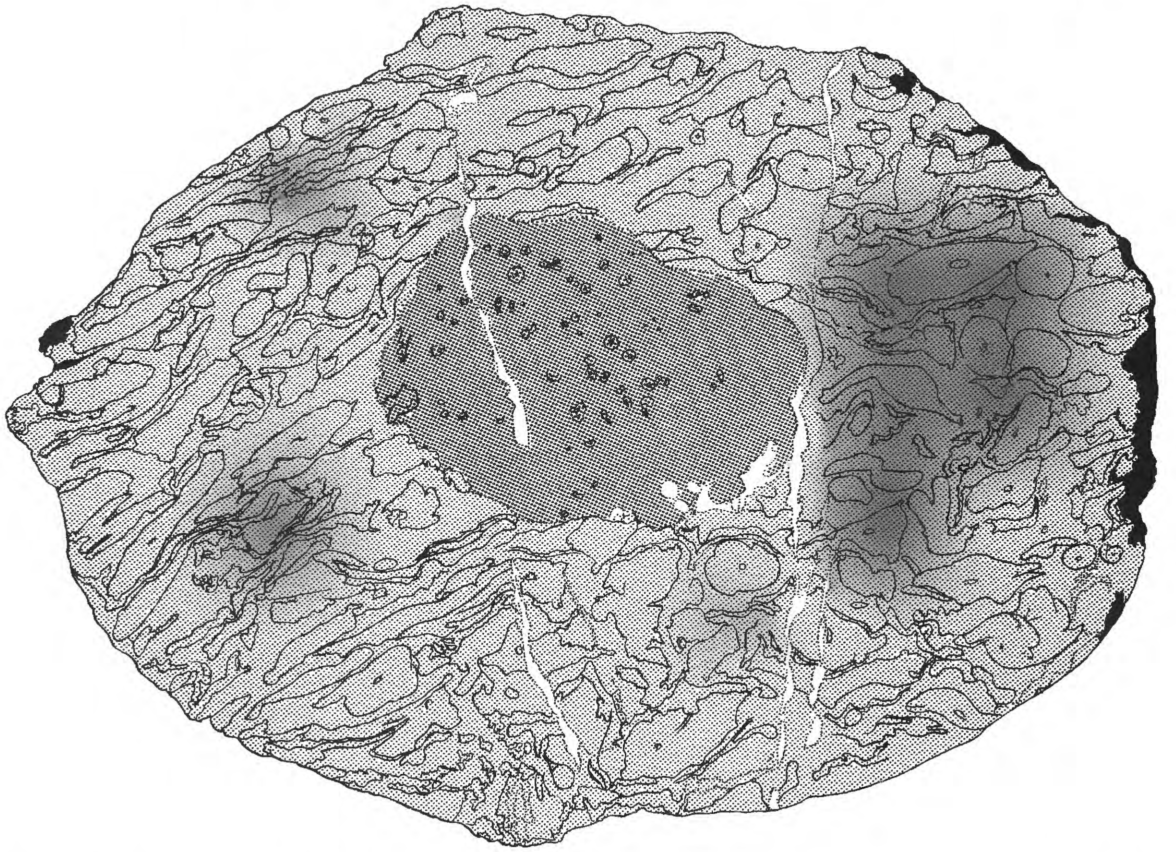

FIGURE 45.—Sketch of sawn surface of a heterogeneous-mixed coal ball, drawn from a peel preparation of specimen 9190–2 J. The marine core is indicated by dark stippling; calcite-filled cracks are unstippled. Natural size.

in a film of coal that indicates their original position below the upper limit of the coal seam.

Marine cores may extend nearly to the bottom of the seam. A large mass of coal balls, 2 feet long and 1 foot thick, was found in place by Mamay in 1957, and dug out of the coal. The bottom of this mass lay within an inch of the bottom of the coal seam, and it contains irregularly shaped but distinct cores through its whole thickness. One core reaches the lower surface of the thickest part of the coal ball mass, and thus was originally separated from the underclay by only an inch of coal.

Distinct bedding of the detrital fragments, both plant and animal, was observed within the marine core in several specimens. In one core (pl. 30, fig. 1) the fossil debris is arranged in easily discernible layers. The bedding may be flat and parallel to the less distinct bedding of the plant material in the surrounding normal matrix. However, for about 1 cm from the contact between the core and normal matrix, the bedding of the core is slightly warped. This warping suggests that the original lump of marine mud was still fairly plastic when deposited in the coal swamp. After deposition its inner bulk sagged slightly and produced the warped bedding planes.

Our interest in the specimen shown on plate 30 was increased by two facts: (a) The core itself is a roughly flattened body that stands "on edge" with its bedding planes extending across its smallest dimension. Thus the core presumably dropped into a deep but relatively narrow indentation in the surface of the peat, in such a way that its own bedding planes paralleled the surface of the bog. (b) The layer of coal surrounding this specimen also contains a second small normal coal ball with distinctly layered plant debris. This layering, however, is nearly perpendicular to that of the mixed specimen and indicates a precoalification disturbance of the peat, which distorted the bedding plane relations between these two adjacent coal balls.

The Berryville material is also distinctive because of its faunal content. As far as determinable, the faunas of the cores contain several elements identical with animals found in the limestone overlying the coal seam. The cores also contain many spores, cuticular fragments, and other plant remains. Although several samples of normal matrix surrounding the cores were carefully trimmed away from the latter and dissolved in acid, these samples produced no animal remains. It is therefore evident that the cores and surrounding normal matrices could not have been formed under identical depositional conditions. Further support for this line of reasoning may be seen in the results of chemical analyses of the two matrices (p. 207; table 2). These show that the Berryville core material contains Al_2O_3, which does not occur in the normal matrix or in any of the coal balls analyzed.

FAUNAL COAL BALLS

Specimens of faunal coal balls were noted in significant numbers only at the Monmouth, Kans., locality. They conform with the essential features of normal coal balls except that the contained fossils are of exclusively zoological origin. In shape they vary almost as much as normal coal balls, but have perhaps a higher proportion of lenticular or flattened specimens. Baxter (1957, written communication) noted that many of them are of sheetlike aspect. Their faunal contents may be roughly layered or scattered at random through the matrix, which may also contain stringers of coal. The animal remains are mostly small pyritized brachiopod fragments. As shown in tables 1 and 2, coal balls from this locality usually contain more pyrite than those from any other locality investigated.

CHEMICAL ANALYSES

In order to determine what chemical differences exist between normal and mixed coal balls, eight typical samples were selected for semiquantitative spectroscopic analysis and rapid rock analysis as described by Shapiro and Brannock (1956). The rock analyses were performed on samples as received, without preliminary drying. Samples of both normal and mixed coal balls were taken from West Mineral, Kans., McAlester, Okla., and Berryville, Ill.; a faunal coal ball from Monmouth, Kans., was analyzed. The Berryville material also included one sample from a heterogeneous-mixed coal ball and a piece of the limestone over the channel in the coal seam.

The rapid rock analyses (table 2) show some apparently consistent but small differences between normal and mixed coal balls in concentrations of SiO_2, FeS_2, K_2O, P_2O_5, Al_2O_3, $CaCO_3$ ($CaO+CO_2$) and MgO. These could reflect chemical makeup of animal fragments or other uncontrollable factors, and cannot safely be considered significant. The complete results are, however, presented as tables 1 and 2, for they represent the most detailed coal ball analyses known to us.

In reviewing the published record we found several chemical analyses of coal balls in papers treating primarily of the fossil floras. References to these are given to aid those who may wish to pursue the problem of the formation and chemical composition of coal balls. Analyses published prior to 1908 were summarized by Stopes and Watson (1908). An analysis of a single coal ball from Bohemia was presented by Kubart (1911, p. 1038). Leclercq (1925, p. 21) published one analysis of a coal ball from Belgium and subsequently analyses of three others (Leclercq 1952, p. 398). Zalessky and Tchirkova (1931, p. 590) published an analysis of a coal ball from the Kousnetzk basin of Russia. Teichmüller, Teichmüller, and Werner (1953, p. 145) published a summary of their work and that of others; they listed a dozen analyses for iron oxide, calcium carbonate, and magnesium carbonate in coal balls or "Torfdolomit" from the Ruhr area of Germany. So far as is known, Darrah (1939, p. 132) has presented the only published analysis of a coal ball from the United States.

TABLE 1.—*Semiquantitative spectroscopic analyses of coal ball and limestone samples*

[Analysts: Mona Frank and P. L. D. Elmore. Phosphorus may be present in these samples, but further work is necessary to assure positive identification. Sensitivity for phosphorus is 0.1]

Percentage	West Mineral, Kans., Fleming coal		Berryville, Ill., Calhoun coal			McAlester, Okla., Secor coal		Monmouth, Kans., Bevier coal
	Sample 145717, normal coal ball	Sample 145718, mixed coal ball	Sample 145719, normal coal ball	Sample 145720, marine core from mixed coal ball	Sample 145721, marine limestone above coal	Sample 145722, normal coal ball	Sample 145723, mixed coal ball	Sample 145724, faunal coal ball
>10	Ca	Ca	Ca	Ca	Ca	Ca	Ca	Fe
5–10								Ca
1–5	Fe, Mg	Fe			Mg	Fe, Mg	Fe	
.5–1		Mg	Fe, Mg	Fe, Mg	Al, Fe		Mg	
.1–.5	Si, Mn	Si	Si	Si, Al	Si, Mn	Si	Si, Al	Si, Mg
.05–.1	Al	Al, Mn	Mn	Sr, Na, Mn	Sr, Na		Mn	Al
.01–.05	V, Sr, Na, B, Ti	Sr, V, Na, Ti	Na, Sr, Al	Ba, Ti, V, B	Ba, Ti, V	Sr, Al, Mn, Na, V	Ba, Sr, Na, V	Mn, Na, Sr, Ba, Pb
.005–.01	Ni, Pb	B, Ni	Ti, B, Ni	Ni	B, Ni	B	B, Ti	Cu, Y, V
.001–.005	Ba, Mo	Pb, Cu, Ba	V, Ba	Pb, Cr, Cu, Mo	Cr	Ba, Ti		Mo, Sn, Ti, Zr
.0005–.001	Cr, Cu	Cr, Mo	Mo, Cr, Cu		Cu, Mo	Cr, Mo, Cu	Cr, Mo, Cu	Yb, Cr
.0001–.0005					Ag			

TABLE 2.—*Rapid rock analyses of coal ball and limestone samples*

[Analyst: Paul W. Scott]

Constituent	West Mineral, Kans., Fleming coal		Berryville, Ill., Calhoun coal			McAlester, Okla., Secor coal		Monmouth, Kans., Bevier coal
	Sample 145717, normal coal ball	Sample 145718, mixed coal ball	Sample 145719, normal coal ball	Sample 145720, marine core from mixed coal ball	Sample 145721, marine limestone above coal	Sample 145722, normal coal ball	Sample 145723, mixed coal ball	Sample 145724, faunal coal ball
SiO_2	0.21	0.80	0.35	1.8	2.9	0.31	1.3	1.1
Al_2O_3	---	---	---	.68	1.1	---	.46	---
[1] FeO	1.3	.6	1.0	.9	2.7	.3	2.2	.0
MgO	2.8	1.0	1.8	1.4	2.8	3.4	2.3	.40
CaO	47.5	45.9	51.6	50.2	46.6	48.4	45.6	18.6
Na_2O	.09	.08	.08	.09	.14	.10	.08	.13
K_2O	.01	.03	.03	.09	.15	.02	.06	.06
TiO_2	.01	.02	.02	.03	.04	.02	.02	.01
P_2O_5	.10	.15	.08	.23	.17	.16	.19	.51
MnO	.34	.18	.27	.18	.47	.08	.18	.05
H_2O	.73	.50	.59	.36	.76	1.2	.52	.86
CO_2	40.5	37.1	42.4	40.4	40.2	40.8	39.7	14.5
Total S as FeS_2	4.5	11.2	.60	3.0	1.0	1.8	4.7	60.9
Total [2]	98	97	99	99	99	97	97	97

[1] Iron, exclusive of that required for calculation of FeS_2, calculated as FeO.
[2] Organic matter contained in all samples may account for differences between totals and 100 percent.

LABORATORY METHODS

Mixed coal balls from each of the various localities possess more or less distinctive physical and biological characteristics. To demonstrate these differences, a number of coal balls, as well as samples of associated rocks are described on pages 217–222. Faunal contents of the samples and spore identifications are summarized in table 3. Although small isospores or microspores were observed and are apparently abundant in some of the residues, these were not identified, because the larger spores were sufficient demonstration of the intermixture of land plants with marine animals.

Though animal remains in coal balls may easily be seen on cut or broken surfaces, such examination gives a generally incomplete picture of the biological composition of the assemblage. For this reason acid solution was used as the chief technique for releasing fossils from the coal-ball matrix.

When animal remains were first noted in the collection briefly described in 1953, commercial grade hydrochloric acid was used to isolate pyritized remains from the matrix. However, the diversity of animal groups represented in these residues suggested the presence of phosphatic fossils such as vertebrate bones, teeth and scales, and conodonts. Formic acid therefore was substituted for hydrochloric in our later studies, with the result that phosphatic fossils were recovered from many of the mixed coal balls.

Coal balls selected for acid solution were sawed into 1-inch thick slices; part of each coal ball was held in reserve for additional preparations if later desired. Because most of the fossils seen on the smoothed surfaces were relatively small, the slabs selected for acid solution were broken into small pieces to speed the reaction. Where it was evident that larger fossils were contained in the matrix, entire slabs were dissolved. Before the cores of marine sediment in the Berryville, Ill., coal balls were dissolved, surrounding normal parts were trimmed from the core so that the insoluble residue would not be contaminated with plant material from the normal coal ball matrix.

The samples were then weighed and placed in formic acid in covered containers. Strength of the acid was adjusted to prevent effervescence from damaging fragile specimens, and was maintained by daily recharging of the solution. Most samples required 7 to 10 days for complete solution of their soluble components. Samples high in calcium carbonate were generally reduced to fine- or medium-textured granular residues, but some with large amounts of pyrite were deeply corroded but not entirely disaggregated. The latter contributed little to faunal analyses because of generally poor preservation of the fossils.

The residues were washed in water, allowed to dry, and weighed to determine the proportions of soluble and insoluble components of the original sample. The residues were then sized through standard-size sieves down to 200-mesh size; this was done under water to keep breakage at a minimum. The graded residues were then dried and picked. In addition to the mixed coal balls, samples of limestone caprock, of normal coal balls, and of the normal matrix surrounding cores in the Berryville, Ill., specimens were also dissolved.

Samples from Berryville, Ill., were the most soluble: their residues ranged only from 0.2 to 5.4 percent of original sample weight. At the other extreme, residues of samples from Monmouth, Kans., ranged from 22.6 to 37.9 percent of sample weight. Because the solubility of the different samples showed meaningless variation, further details are omitted.

TABLE 3.—*Distribution of animal groups and large spores in insoluble residues*

Samples 9189–119 and 9190–1 were not etched in order to preserve calcareous coral specimens.
Locality of samples: E–1, 2, 17, Franklin, Kans.; 9189–119, E–9, 10, 12, 18, 23, 24, West Mineral, Kans.; E–7, 8, 20, 21, Monmouth, Kans.; E–11, 22, 30, 31, McAlester, Okla.; E–13, Oskaloosa, Iowa; E–3, 4, 19, 25–29, 9190–1, Berryville, Ill.; E–14, limestone overburden, West Mineral, Kans.; E–16, limestone overburden, McAlester, Okla.; E–5, limestone in channel, Berryville, Ill.; E–6, limestone overburden, Berryville, Ill.; E–15, limestone below channel, Berryville, Ill.

Fossil	Type of deposit and sample number																																
	Homogeneous-mixed coal balls													Heterogeneous-mixed coal balls							Normal coal balls						Faunal coal balls		Miscellaneous associated sedimentary deposits				
	E–1	E–2	9189–119	E–9	E–10	E–12	E–23	E–24	E–20	E–11	E–22	E–31	E–13	E–3	E–4	E–25	E–26	E–27	E–28	E–29	9190–1	E–17	E–18	E–21	E–19	E–30	E–7	E–8	E–14	E–16	E–5	E–6	E–15
Protozoa:																																	
Ammovertella? *inclusa* Cushman and Waters														X																			
Ammovertella cf. *A. labyrintha* Ireland						X																											
Ammovertella? aff. *A. prodigalis* Ireland																															X		
Ammovertella sp							X				X				X			X	X	X											X	X	
or *Serpulopsis* sp								X			X				X																		
Ammovertella? sp							X							X		X		X															
or *Glomospira* sp																																X	
Genus aff. *Ammovertella*														X	X																	X	
Apterrinella sp								X								X	X		X	X											X		
or *Calcitornella* sp																		X															
Apterrinella? sp						X									X			X	X	X													
Cornuspira? sp	X																										X						
or *Glomospira* sp																											X						
Cornuspira? sp									X																								
Endothyra or *Endothyranella*? sp																											X						
Endothyranella powersi? (Harleton)																X																	
sp																											X						
Globivalvulina sp																													X	X			
Glomospira sp									X									X															
Serpulopsis aff. *S. insita* (White)							X																										
Serpulopsis? sp																				X													
Tetrataxis pauperata? (Worthin)	X																										X						
Thurammina aff. *T. rectangularis* Ireland																X		X															
sp																X																	
Thuramminoides sp																																X	
Fusulinids indet											X	X					X												X	X		X	
Porifera:																																	
Cf. *Fissispongia*? sp							X																										
Hexactinellid spicule																X				X													
Coelenterata:																																	
Lophophyllid coral			X																		X												
Echinodermata:																																	
Crinoid stems	X	X					X									X		X	X	X							X				X		
Annelida:																																	
Arabellites sp																																X	
"*Spirorbis*" sp						X				X	X	X				X				X													
Bryozoa:																																	
Ramiporalia sp																X			X														
Trepostomatous bryozoans indet										X				X		X	X		X												X		
Fenestella sp														X		X	X	X	X	X													
Polypora sp 1																	X	X													X		
sp 2																		X															
sp 3																X																	
Penniretepora sp 1														X	X	X	X	X	X	X											X		
sp 2																X				X											X		
Septopora sp											X																						
Rhabdomeson sp														X		X																	
Rhombocladia sp														X		X	X	X	X	X											X		
Rhombopora sp														X		X	X	X	X	X											X		
Brachiopoda:																																	
Linguloid indet											X	X								X													
Orbiculoid indet						X					X									X													
Rhipidomella? sp																	X										X						
Derbyia sp							X																										
Mesolobus sp	X																										X						
Chonetid indet		X				X		X											X														
Marginifera sp						X																											
Productoid indet					X	X	X	X						X		X	X	X	X	X									X		X		
Mollusca:																																	
Nuculana sp																				X													
Nuculoid indet																											X						
Parallelodon sp							X	X	X	X	X	X				X	X			X													
Septimyalina sp	X									X	X	X																					
Cf. *Leiopteria* sp				X			X			X	X	X				X				X													
Schizodus sp							X			X						X	X												X				
Aviculopecten sp																	X																
Pectinoid indet								X																									
Mytilid indet										X	X	X								X										X			
Permophorus sp							X			X	X	X				X																	
Astartella sp							X							X			X		X	X													
Pelecypods undet							X	X		X									X											X			
Pelecypods indet						X	X	X	X	X	X	X	X		X	X														X			
Knightites (*Retispira*) sp						X			X																			X					
Bellerophontid indet	X	X											X		X	X																	
Borestus sp									X																								
Glabrocingulum sp						X	X																				X	X					
Neilsonia? sp									X																								
Shansiella sp					X				X		X	X				X			X	X							X	X					
Steinkern cf. *Shansiella*							X	X					X					X									X	X					
Pleurotomarian indet	X						X			X		X				X	X			X							X	X	X				
Cf. *Microdoma* sp										X	X	X								X													
Eucochlis sp							X	X			X		X														X						

TABLE 3.—*Distribution of animal groups and large spores in insoluble residues*—Continued

Fossil	Type of deposit and sample number																															
	Homogeneous-mixed coal balls												Heterogeneous-mixed coal balls						Normal coal balls					Faunal coal balls		Miscellaneous associated sedimentary deposits			
	E-1	E-2	9189-119	E-9	E-10	E-12	E-23	E-24	E-20	E-11	E-22	E-31	E-13	E-3	E-4	E-25	E-26	E-27	E-28	E-29	9190-1	E-17	E-18	E-21	E-19	E-30	E-7	E-8	E-14	E-16	E-5	E-6	E-15
Mollusca—Continued																																
Naticopsis? sp																										X						
Paleostylus (*Pseudozygopleura*) sp 1								X							X	X											X						
(*Pseudozygopleura*) sp 2																										X						
Cf. *Bulimorpha* sp					X	X			X			X															X	X					
Meekospira sp								X																			X	X					
Girtyspira sp								X			X															X	X					
Subulitid indet	X	X								X						X	X												X					
Donaldina sp						X	X	X	X	X	X					X			X	X								X					
Steinkern cf. *Donaldina* sp				X	X						X	X					X	X													X		
Low-spired gastropod indet		X								X	X		X	X	X	X		X		X							X	X		X	X	X	
High-spired gastropods indet											X	X				X			X														
Cf. *Endolobus* sp							X																									
Mooreoceras sp							X																									
Pseudorthoceras knoxense (McChesney)												X																				
Arthropoda:																																
Ditomopyge sp														X		X	X	X	X	X												X	
Cavellina sp											X																					
Bairdia cf. *B. rhomboidalis* Hamilton																	X														X		
cf. *B. pompilioides* Harlton											X																					
cf. *B. garrisonensis* Upton of Kellett											X																					
sp	X										X	X	X			X	X			X							X		X				
Bairdia? sp										X																			X					
"*Bairdia*" cf. "*B.*" *oklahomensis* Harlton		X																														
aff. "*B.*" *texana* Harlton																	X		X									X				
sp																															X		
Bairdiacypris? sp																				X												
Fabelocypris sp										X	X	X																					
Healdia sp											X					X				X							X	X					
Paraparchites? sp											X								X												
Sansabella sp										X																						
Sansabella? sp											X	X				X				X												
Monoceratina sp													X																			
Kirkbya sp													X				X			X												
Kirkbya? sp																													X				
Knightina sp											X					X																
Amphissites centronotus (Ulrich and Bassler)													X	X		X			X										X		X		
sp																				X												
Kegellites cf. *K. dattonensis* (Harlton)															X																	
Kellettina? sp																			X													
Glyptopleura sp	X	X																														
Hollinella sp	X					X	X			X	X	X	X			X	X		X	X							X		X				
Genus indet A																													X				
Genus indet B																													X				
Genus indet										X							X		X	X												
Chordata:																																
Acanthodii											X																X					
Cladoidachii											X			X	X		X		X								X	X					
Solachii						X																										
Pleurocanthoidii											X						X										X					
Bradydonti											X																					
Actinopterygii	X	X							X	X	X																X	X		X			
Fish remains indet							X					X	X							X											X	
Conodonts:																																
Hindeodella sp											X																					
Ozarkodina delicatula (Stauffer and Plummer)															X																	
Ozarkodina sp																X																
Neoprioiodus sp																										X						
Roundya cf. *R. subacoda* (Gunnell)																										X						
Spathognathodus minutus? (Ellison)																X				X												
Gnathodus roundyi Gunnell																										X						
bassleri (Harris and Hollingsworth)													X																			
sp		X																														
Cavusgnathus flexa Ellison											X					X																
Idiognathodus magnificus Stauffer and Plummer											X															X	X					
cf. *I. magnificus* Stauffer and Plummer	X	X																														
Streptognathodus elegantulus Stauffer and Plummer														X	X	X															X		
Barlike conodont indet	X			X							X						X			X												
Platelike conodont indet									X		X																					
Bladelike conodont indet																X																
Large spores:																																
Cystosporites varius (Wicher) Dijkstra												X								X												
sp													X																			
Monoletes ovatus Schopf						X	X		X				X	X	X	X				X		X	X		X	X							
Parasporites cf. *P. maccabei* Schopf														X																		X
Spencerisporites sp				X	X	X	X						X	X	X	X		X	X	X		X	X		X				X		X		X
Triletes auritus Zerndt						X			cf.	X																cf.[1]							
auritus var. *grandis* Zerndt												X	X	X	X	X	X	X	X	X											X		X
glabratus Zerndt														X	X	X	X	X	X	X											X		X
cf. *T. rugosus* (Loose) Schopf										X	X	X								X						X						
cf. *T. superbus* Bartlett				X	X	X	X	X					X																			
triangulatus Zerndt				X		X	X	X				X	X	X				X		X	X											
sp																													X				
Large spore resembling *Lycospora*																															X		

[1] Specimens probably conspecific, but not complete enough for positive identification.

The technique described allows recovery of all but calcareous specimens. In order that important faunal elements should not be overlooked, nonpyritic specimens exposed on fractured surfaces were prepared for identification by mechanical methods. Most of the animal remains recovered by this method are pyritized; the calcareous ones constitute a minor element and consist largely of brachiopods and crinoid columnals.

It is probable that some specimens were destroyed or escaped observation during preparation. Nevertheless a sufficiently wide variety of animal groups are repeated in several coal balls from the same locality to favor the probability that most of the faunal elements are known.

PRESERVATION OF THE FOSSILS

Preservation of the plant fossils needs little discussion because, as is usual in coal ball petrification, there is little if any replacement of the original substance of cell walls. Woody tissues owe their excellent preservation to an impregnation and filling of the cell interiors, the dominant impregrating material usually being calcite. Waxy spore coats and cuticles, among the most resistant substances in the plant kingdom, are ordinarily preserved practically unchanged.

Most of the megaspores recovered from the acid residues are so little distorted by compression that their original shapes and external morphological features may be satisfactorily studied (pl. 33). Those from Berryville, Ill. (pl. 33, fig. 17), McAlester, Okla., and Oskaloosa, Iowa, are seen to be hollow when their coats are broken, a condition that we ascribe to dissolution of the original calcareous fillings of the spore cavities during treatment with acid. Megaspores from West Mineral, Kans., however, may be recovered in a hollow condition or their interiors may contain mineral fillings, usually calcitic, rarely pyritic (pl. 33, figs. 8, 9). The fact that some of the calcitic fillings remained intact after several days' treatment with acid can only be due to exclusion of the acid from contact with the surfaces of the filling, by the intact and impervious endosporal membrane or exospore, or by both. Specimens of *Triletes* cf. *T. superbus* recovered from the same coal ball were either hollow or were filled with pyrite or calcite.

Some of the megaspores are so well preserved that their endosporal membranes can be dissected out. Membranes removed from specimens of *Triletes* cf. *T. superbus* are thin and delicate, and almost invariably show a pattern of regularly distributed and shaped dark spots (pl. 33, fig. 10). The spots, which may represent vestiges of cellular organization, are always restricted to the proximal part of the membrane, and more concisely, to the circular area that is delimited by the arcuate ridges connecting termini of the triradiate sutures of the exospore. On the basis of their proximal positions these spots, despite their abundance in any one spore, were first interpreted as the remains of archegonia, but perhaps they are equivalent to the papillae in similar membranes of *Duosporites* described by Høeg, Bose, and Manum (1955).

Animal remains from most localities are generally replaced by pyrite, but preservation may also be calcareous, phosphatic, or baritic. Only in conodonts, scolecodonts, and fish is evidence of replacement lacking. Both conodonts and fish parts are phosphatic. The few scolecodonts found are black, highly lustrous, and resistant to all the common acids. They are apparently the original chitinlike substance.

Five other groups—the bryozoans, ostracodes, trilobites, worm tubes, and sponges—are consistently preserved in pyrite, almost invariably by replacement, but the few corals found remain calcareous. In the pyritic specimens, replacement ranges from fine to coarse grained.

Preservation of foraminifers is siliceous or pyritic. The thuramminids and tolypamminids had hard agglutinate shells, and in the acid residue the silica sand of many shells remains coherent because of silica cement which may be of secondary origin. The globivalulinids, originally calcareous, were not noted in other than pyritic preservation or chamber fillings. The fusulinid shells are mostly unaltered but their chamber fillings are pyritized or partly silicified.

Aside from the linguloids and orbiculoids, which are phosphatic and do not appear to be replaced, brachiopods from the West Mineral, Kans., samples are unaltered and require mechanical preparation; a few are, however, preserved in pyrite. All those from Monmouth, on the other hand, are pyritized.

Mollusks are present in all the faunas investigated. Pelecypods and gastropods are conspicuous faunal elements. The pelecypods, with two exceptions, are preserved only in pyrite. Cephalopods are calcareous except for the figured specimen (pl. 34, fig. 29). Mineralogic composition of this one was not determined because to do so would necessitate destroying part of the specimen. The specimen is insoluble in hydrochloric acid.

Preservation of the gastropods is perplexing. Although specific identifications are difficult because of the quality of the preservation, there is no apparent correlation between biological identity and mode of preservation of the gastropods. They may be preserved as actual shell replacements or as steinkerns; steinkern preservation of some pelecypods and foraminifers has been seen but not of the other animals observed. Steinkerns may be phosphatic or pyritic and may fill calcareous shells, as shown by hollow casts surrounding the steinkerns on etched surfaces. Shell replacements are pyritic and filled with calcareous material, as shown by the hollow interiors of shell replacements recovered from the residues. Pyritic replacements are most common, but in one sample (Monmouth, Kans., E–20) replacements are composed of barite. A single coal ball may yield different individuals certainly of generic and probably of specific identity in all the types of preservation noted.

One further point with regard to the animal remains deserves mention here—the size of fragments or whole specimens, exclusive of those of ostracodes and conodonts. With the occasional exception of *Derbyia* and productoid brachiopod shells which may reach 3 cm or more in width, most of the animal material consists either of complete individuals or of fragments smaller than 1 cm in maximum measurement; more than half are 0.5 cm or less.

It is probable that mechanical sorting by wave or current action before original sedimentation and subsequent translocation to the swamp is the explanation for the consistently small size of animal fossils found in the coal balls and that the residues are not a representative sample of typical Pennsylvanian marine faunas.

Few of the specimens show evidence of abrasion or mechanical wear, and some of the more intricately ornamented ostracode shells are perfectly preserved. The one group in which worn specimens are common are the fish remains. The rounded corners and edges of many scales and dermal plates suggest considerable abrasion before final deposition.

Representative suites of plant and animal remains recovered from the acid residues are shown in plates 33 and 34, respectively. Plant material was photographed as recovered from the residues, without further chemical treatment.

INTERPRETATION OF ANIMAL-CONTAINING COAL BALLS

Because the marine animal remains contained in the mixed and faunal coal balls cannot be regarded as indigenous to the coal swamps, a fundamental conflict with commonly accepted theories of coal ball formation arises. Normal coal balls are considered by most authors to represent concretions formed in place, in accord with the conclusions of Stopes and Watson (1908). At variance with that hypothesis, however, Kindle (1934) preferred to compare coal balls with the so-called lake balls—mechanically accretionary, spheroidal masses of plant material whose formation has been observed in Recent aquatic environments. Kindle's analogy has not met with popular acceptance (Schopf, 1949, p. 81), but it is possible that his explanation may contain some acceptable points if applied to mixed coal balls. Obviously, any explanation of marine organisms in nonmarine strata must involve transportation of material. Rafting of coals has been suggested in explanation of the phenomena described here, but this explanation is highly improbable in view of the otherwise normal sedimentary relations of the coal seams that provided the mixed assemblages.

Some coal seams locally contain exotic materials such as igneous boulders and pebbles, and although these attract much interest, there seems to be no agreement regarding the mechanisms responsible for such inclusions; cataclysmic transportation, however, is a frequently suggested mechanism. The following discussion by Whitehead and others (1952, p. 290) demonstrates the necessity for resorting to unusual depositional circumstances by way of explanation.

W. L. Whitehead: A 15- or 20-foot tidal wave is not uncommon on some coasts during hurricanes or tsunamis. At these times submarine plants with hold-fasts can carry a 6-inch boulder 10 miles.

J. M. Schopf: Well, that certainly is a possibility. I should say that a number of these freakish and very difficult-to-explain occurrences must be explained by some cataclysmic method of the sort. I am not at all sure that the widespread partings aren't in that category too.

I. A. Breger: Shouldn't you get occasionally some marine evidence?

J. M. Schopf: You would think so—but let me tell you of an occurrence which puts the "shoe on the other foot." I have found coal-ball limestone, that is, the limestone characteristic of coal balls which must have originated no higher than within the upper portion of a coal-measures peat deposit—such coal-ball limestone has been found embedded in an unquestionable marine coquina overlying the coal. This is an example of the reverse direction in transportation. The coal-ball limestone must have originated within the precoal peat bed and then have been transported bodily into the marine bed above it. There are some strange things associated with coal.

We regard the animal-containing coal balls as representative of the "marine evidence" sought by Breger.

HETEROGENEOUS-MIXED COAL BALLS

The Berryville cores or marine inclusions are considered best explained by a transitory force that introduced them into the accumulating peaty plant debris. The evidence for this hypothesis is the complete embedment of the inclusions within the coal balls, apparently without interruption of coal deposition. The following possible physical setting and sequence of events is visualized in explanation of the origin of the cores:

The coal swamp lay at or near sea level and was perhaps separated from the sea only by a low narrow strand barrier, which was sufficiently high to prevent access of marine waters to the swamp environment through normal tidal action. Offshore in shallow waters, a calcareous mud was accumulating, into which both marine animals and bits of plant material, either windblown or drifted, were being incorporated. The animal remains, as demonstrated by their consistently small size, were probably being transported from farther offshore sites of original deposition by currents, the larger representatives of the fauna being sorted out during transportation and only rarely being brought landward, or being brought in only as smaller fragments.

As previously mentioned, each insoluble residue of Berryville core material contains many spores, bits of wood, cuticles, and other plant parts. Except for the spores, many of which are complete and undistorted, the plant material is fragmentary. If the cores do represent transported samples of the sea bottom, then the plant debris included in the cores represents a part of the original organic constituents of the marine mud, and as such must be interpreted as twice-transported matter. The plant material may have been blown to sea by the wind or may have drifted out on the surface; eventually it became waterlogged and sank to the bottom to intermingle with the accumulating animal debris. As the spore contents decayed, the spore interiors were filled with minerals, so that they underwent little or no compression before final calcareous cementation. Finally, the plant material was transported back to the coal swamp, perhaps coming to rest many miles from the area in which it had originally been produced. However, it may also be that a short distance, as well as a short time lapse, for both translocations was involved, because some of the most conspicuous spores in the core material (*Triletes glabratus*, *T. auritus* var. *grandis*, and *Monoletes ovatus*) also occur abundantly in the normal coal balls from this locality.

Occasionally lumps of the semiconsolidated mud were dislodged from the sea floor by tidal currents or by other relatively minor disturbances and were worn into various shapes by wave action; some of these lumps assumed cylindroid shapes, some were more irregular.

Violent storms created unusually large waves that swept inland and inundated the swamp. The waves carried along the cylindroid wave rollers as well as less regularly shaped lumps of mud that contained both animal and plant remains. The mud lumps were deposited on the irregular surface of the peat, or fell through the upper layers. A firm consistency of the mud lumps is implied by the discrete nature of the cores and the angularity of some of the cross sections. However, parts of the mud lumps were sufficiently soft that intermixture with the adjacent peat occurred locally, and some of the firmer plant fragments penetrated the surfaces of the lumps.

The core shown in figure 45 is oriented parallel to the mass of roots that constitutes the normal matrix. The roots, preponderantly alined in the same direction, probably created a series of nearly parallel grooves on the surface of the peat, and minor agitation of the receding water could have caused the core to settle in one of the grooves. Meanwhile the turbulence also dislodged chunks of peat, redeposited them, and in some instances effected a reorientation of their original bedding planes. Evidence for this reorientation is apparent in the specimen shown in plate 30, figure 1, where the bedding of plant material in the small coal ball fragment within the coal matrix at the right is oriented nearly at right angles to that of the larger specimen containing the marine core. The same specimen shows evidence that deposition of the marine material was sudden, rather than gradual and protracted, for the plant material beneath the lump is compacted and bedded parallel to the rounded contours of the bottom of the lump, while the plant material in contact with the sides of the lump shows evidence of shearing.

Marine waters soon retreated. Upon restoration of the normal swamp environment, continued peat deposition covered the foreign marine mud-lumps and enclosed them within the plant debris.

Lithification of the mixed coal balls, just as of normal ones, preceded final compaction and coalification of the peat, as demonstrated by the direction of lamination of the coal in relation to layering in the heterogeneous-mixed coal balls and by the uncompressed condition of material within the coal balls. Concretionary action was probably responsible for calcareous preservation of plant debris and its cementation to the marine core.

While the summary above possibly represents an oversimplification of events, we believe that it best fits the evidence on hand.

In seeking to explain the slender cylindroid forms of some of the Berryville cores, let us consider an analogous modern erosional phenomenon. Along the western shore of Chesapeake Bay in Maryland are steep cliffs of the Miocene Calvert formation, including beds of blue clay. In the area south of Chesapeake Beach, large blocks of the clay occasionally slump into the water. Wave action erodes these blocks into smaller lumps, some of which eventually are thrown onto the beach. Among these lumps some specimens are worn into long, roughly cylindroidal shapes. One, collected in 1952 by Jack E. Smedley, is a straight rodlike lump, 8 inches long, 1½ inches wide, and ½ inch thick, with an oval cross section; its width and thickness are nearly uniform, and it is abruptly rounded at either end. This rod is similar in shape to the core illustrated in plate 31, figure 1.

Occurrences of similar clay balls and boulders were reported by Grabau (1913, p. 711–712) and by Richter (1926). They reported the boulders to have been formed under water and sometimes to be encrusted with marine shells that became embedded as the balls rolled over shell-containing sands. The "schlickgerolle" observed by Richter on the coast of the North Sea are sometimes cylindroid.

Analogous modern sedimentary material has been reported in several recent papers. Armored mud balls, described from Ventura County, Calif. (Bell, 1940), provide a striking example of the effects of currents in abrading chunks of mud into symmetrical forms; many observed by Bell were nearly spherical in shape. The armor of these balls, although consisting chiefly of pebbles, illustrates the ability of rolling mud masses to accumulate foreign debris through mechanical accretion. An important observation, in regard to the content of the armor, is that "frail gastropod shells were occasionally as perfectly preserved as though they had been packed in cotton" (Bell, 1940, p. 18); this fact may in part explain the undamaged condition of the ostracodes and conodonts found in the mixed coal balls.

A paper by Kindle (1937) contains descriptions of an even more appropriate modern analog of the mixed coal balls. Kindle observed that after the Atlantic coast hurricane of mid-September 1936 "boulderlike masses of tenaceous lagoon clay bound firmly together by salt grass roots were seen widely scattered over the flat surface of a lagoon island" (Kindle, 1937, p. 433) at an inlet a few miles southwest of Atlantic City, N.J. In regard to marine shells in many of the boulders, he stated that "these recent fossils do not represent a veneer of shells attached to the surface by rolling about. They have clearly been entombed in the sediments as they were laid down near the shore of the inlet or bay. From the original bed these mud boulders have apparently been separated by undercutting of currents in lagoon channels and the lifting power of waves."

Perhaps the best documented study of effects of a severe storm on a low-lying coast is that made following hurricane "Audrey," which struck southwestern Louisiana on June 27, 1957 (Morgan, Nichols, and Wright, 1958). Two large arcuate masses of marine mud, each more than 2 miles long and 1,000 feet wide, were driven between 1,100 and 1,250 feet inland. Tidal salt water extended more than 30 miles inland, and some areas were still inundated 3 weeks after the storm struck.

An older analog was described in some detail by Croneis and Grubbs (1939). They reported subspherical calcareous nodules containing assemblages of silicified marine animal fossils in dolomitic beds of Silurian age near Chicago, Illinois; they interpreted these nodules as mechanical accretionary structures formed by the action of storm waves on clastic calcareous muds in relatively shallow sea waters.

Although other descriptions of clastic balls have been published, the foregoing selected examples illustrate the points of emphasis in our interpretation of mixed coal balls. Under certain circumstances, wave or current action does dislodge chunks of plastic sediments, wears and deforms them, and transports them to new environments; it also forms similarly shaped masses through mechanical accretion and transportation. In either instance the remains of organisms may be incorporated within the sediment. It is the shaped chunks of plastic mud that we compare with the Berryville cores.

HOMOGENEOUS-MIXED AND FAUNAL COAL BALLS

The homogeneous-mixed coal balls from Kansas, Oklahoma, and Iowa are of less obvious origin than the Berryville, Ill., specimens because of their less clearly delineated structural features. Nevertheless, we believe that they can be attributed to a series of events and a physical environment similar to that suggested above. Most of the Kansas homogeneous-mixed coal balls, and perhaps all of those from Oklahoma, may best be considered analogous to the core of a Berryville, Ill., specimen. They may represent transported marine mud lumps whose chief difference from the Berryville cores is that they usually are directly enclosed by coal rather than by a layer of petrified plant material. The presence of varied marine faunas within the coal is, of course, the primary evidence of transportation, but the texture of some mixed coal balls is also worth consideration.

The swirled texture of some of the homogeneous-mixed coal balls may be regarded as evidence of prelithification rolling of fossiliferous mud lumps. The swirls are usually irregularly ovoid; they are sometimes vaguely marked and are often accompanied by thin stringers of decomposed plant material which extend for some distance into a nodule. More important, the swirls are primarily effects of animal shell fragments oriented with their flatter surfaces more or less parallel along curved lines (pl. 27, fig. 4). This alinement may be the result of adhesion of shell fragments to the surface of a rolling mud lump, or may be secondary orientation by pressure on the enclosing matrix. Presence in a few mixed coal balls of two or more distinct sets of swirl markings may indicate adhesion of several originally separate mud lumps that were indurated, after deposition in the swamp, by additional calcium carbonate and pyrite.

Still other homogeneous-mixed coal balls may actually be more closely comparable to the Berryville cores, although not texturally so clearly delineated. Some of these contain pockets of marine fossils, which may lie either well within the coal ball or only along its periphery and which merge vaguely with areas containing only plant material. These pockets suggest an origin similar to that of the Berryville cores: that is, marine mud lumps deposited on the surface of the peat and ultimately incorporated along with some of the peat into the same coal balls. Before lithification, however, partial solution of the calcareous mud lumps may have occurred and permitted some intermingling of the marine animals and the surrounding peat.

Several processes are considered possible for formation of the rare specimens, such as the one from Oskaloosa, Iowa, in which an ostensibly normal coal ball contains a sparse marine fauna with no physical evidence of enclosing marine sediments. A small lump of transported mud may have been dissolved chemically or dispersed by gentle current action after deposition in the coal swamp; such action would have released the enclosed animal remains, which sank into the spongy peat mass and eventually became part of an otherwise normal coal ball, formed through concretionary growth. Another possible explanation is that disintegration of mud lumps during transportation could have released the contained fossils as the waves passed over the coal swamp; again exotic animal remains would have been incorporated in coal balls. A third possibility is that the shells were introduced as clastic particles in a mud slurry. Perhaps some of the animals thus introduced into the coal swamp were actually living at the time of inundation, and were swept along as part of the foreign debris. However, the foraminiferal-incrusted inner surfaces of many of the shells in the Kansas and Illinois coal balls indicate that the animals were dead before deposition in the coal swamp.

Striking evidence of twofold transportation of plant material is found in the Kansas mixed coal balls. Some residues contain abundant tests of serpulopsid foraminifers, a generalized and simple, irregularly tubular adherent type. These tests are commonly adherent on the associated invertebrate shells (pl. 34, fig. 46) but are also found on plant debris (pl. 33, figs. 25–30). They are most common on the large megaspore species *Triletes* cf. *T. superbus*, where they occur on both the outer and inner surfaces of the spore coat (pl. 33, figs. 27–30). That these occurrences are not accidental juxtapositions is shown by the exact conformity of the foraminiferal tests with the spherical contours of the spore surfaces. The foraminiferal encrustation of the terrestrial plant material occurred in a marine habitat, and there seems no alternative to attributing this association to twofold transportation of the encrusted plant fragments.

The above concept actually strengthens rather than weakens the logic of our interpretation, because transportation of land-plant material from near-shore environments to the open sea and its subsequent deposition on the sea bottom among the remains of marine organisms is a well-known phenomenon. White (1911) summarized from the records of the *Blake*, the *Challenger*, and the *Albatross* several accounts of land-plant debris having been dredged from the sea bottom at depths of as much as 2,150 fathoms.

The Monmouth, Kans., occurrence of mixed and faunal coal balls in the Bevier coal is the most difficult phase of this overall problem to interpret, and one which warrants further and more detailed investigation. The large amount of xenoclastic marine animal debris incorporated in the coal there is obviously a reflection of proximity of coal swamp and sea waters. The plant accumulations may even have lain at the actual strand line at the time of deposition, and have thus allowed more abundant introduction of marine muds into the swamp. Possibly the peat deposit was unusually spongy with large and abundant interstices that became filled with mud lumps before the weight of overburden could compress the peat and cause collapse of the interstices. This process could explain the distribution of the faunal coal balls throughout the thickness of the seam. An alternative hypothesis that the coal itself is an allochthonous marine deposit is disproved by the presence of a well-developed stigmarian underclay. There is no obvious explanation of the scarcity of recognizable plant material in the coal balls, but it may be due to the extreme pyritization, which is several times higher in the monmouth coal balls than in those from other localities and which may have obliterated plant structures that were originally present.

Whatever the origin of the faunal coal balls, it is evident that they were brought about by a very localized set of circumstances, for their occurrence in the Bevier coal has not been sufficiently widespread to attract the attention of previous workers. Although 14 mining localities were visited during his investigations, Hambleton (1953, p. 56) remarked that coal balls occur "only in the Mineral coal" and, furthermore, that nodular pyrite is rare in the Bevier coal.

ALTERNATIVE INTERPRETATIONS

The difficulty of arriving at an interpretation of these mixed coal balls that might be expected to meet with a consensus of approval has been emphasized to us by discussion with several colleagues. Mixed coal balls have been suggested to us to represent filled animal burrows, erratic limestone boulders, or cavities filled by normal sedimentary processes. Although none of these possibilities appeals to us, it seems fitting to discuss each briefly and to present the contradictory evidence.

The animal-burrow hypothesis was suggested chiefly by the appearance of one of the heterogeneous-mixed specimens from Berryville, Ill. This specimen, shown in plate 31, figure 1, contains the most symmetrical marine core found, the core itself being some 16 inches long and 2½ inches in diameter. Its remarkably cylindroid shape is rather atypical of the Berryville cores, but at the same time is somewhat suggestive of an animal burrow. Evidence against such an interpretation follows:

1. The orientation of this particular core is parallel with the primary axis of the containing coal ball and, accordingly, parallel with the bedding of the coal itself. Assuming that such a horizontal burrow was made at a time when marine muds and animal debris were available as a filling substance—after marine encroachment and deposition on the coal swamp surface of marine sediments—complete filling of the burrow would have necessitated horizontal infiltration through a relatively narrow pathway. Moreover, if the overlying sediments were the source of the burrow fillings, the cores and the limestone presumably should have the same texture and fossils. However, the crinoidal fragments in the cores, being relatively well sorted and smaller than those in the overlying limestone, impart a finer texture to the cores. Large spores, which are fairly abundant in the cores, are apparently absent from the overlying limestone.
2. In most of the heterogeneous-mixed coal balls it is impossible to demonstrate sufficient uniformity or symmetry to suggest the origin of the cores as filled burrows. Aside from a few Berryville cores similar to that which suggested filled burrows as a possible interpretation, most of the marine inclusions from that locality are irregularly shaped. Furthermore, animal burrows can scarcely account for the lenticular or irregular shapes of the homogeneous-mixed coal balls from Kansas, or for the unusually large size of some.

The interpretation that mixed coal balls represent indurated erratic boulders analogous to the boulders described by Dix (1942) and Price (1932) from Welsh and American coal beds seems unlikely. If the mixed coal balls represent indurated boulders of fossiliferous limestone that were swept into the coal swamps, it is difficult to explain the lenticular shapes of some specimens. Assuming that the specimens were indurated boulders at the time of introduction into the coal swamp, they would have been resistant to deformation of shape by compaction, and thus must have been lenticular in shape at the time of their deposition, in which case some other physical agency must have shaped them. It seems improbable that they were either torn loose from their source beds as small lenses, or that they were worn into such regular shapes through hydraulic erosion between the times of their derivation and deposition.

Further, in the Berryville mixed coal balls, the contacts between the cores and surrounding normal matrix commonly are sharply definable, but here and there are small areas where the contact is poorly developed and where plant material continuous with that of the normal matrix extends into the core for some distance. The material may be either woody axes that have clearly punctured the core matrix or may be partially decomposed, more or less finely comminuted, plant hash that grades almost imperceptibly into the core. These small areas suggest that at the time of its deposition in the coal swamp, part of the core was sufficiently plastic to allow for some mixture of its substance with the surrounding peat.

The view has been expressed that the mixed and faunal coal balls may be the result of normal sedimentation—that is, that the fossil animals may represent part of the first fauna that entered the drowned coal swamp. Although this view deserves serious consideration, again we regard it as untenable for several reasons:

1. The fossil associations described here and their ecological implications are not normal. Although Pennsylvanian stratigraphy and paleontology, especially of the economically important coal beds, have been studied intensively for over 100 years, to the best of our knowledge no one has previously reported marine invertebrates within the coal seams, except as contained in shale partings. In summarizing contemporary knowledge of American Pennsylvanian sedimentation, Weller (1957, p. 348) noted that "animal fossils, however, are exceedingly rare in coal seams, and those which

do occur almost invariably are preserved in cannel or canneloid layers."

2. Except for channels, "washouts," and rare sedimentary dikes, the upper surface of the coal seam is most commonly a flat surface. Had the upper surface of the coal-forming peat been notably irregular, plugs, sheets, and other irregular bodies of marine sediment should be common in coal seams. If the faunal and mixed coal balls were fillings of surface irregularities through normal sedimentation, they would likely be continuous with the overlying sediments; instead they are discrete bodies buried within the coal and have a vertical distribution throughout the thickness of the seam.
3. The coal on the upper surface of the animal-containing coal balls indicates that peat deposition continued after deposition of the marine inclusions. A permanent marine inundation that would have permitted a marine biota to flourish on the flooded peat surface would have killed the vegetation and stopped peat deposition.
4. In the West Mineral area of Kansas the fauna of the shale above the Fleming coal (Williams, 1937, p. 105) has a different aspect from that of the mixed coal ball fauna, being locally a coquinoid mass of productoid brachiopods.
5. The swirled texture of some of the homogeneous-mixed coal balls, as well as the fragmentary nature of the larger fossils, suggests transportation.

CONCLUSIONS

Studies of animal-containing coal balls suggest four conclusions, enumerated below. Some of these are long-established concepts in coal sedimentology, but they are incorporated here to complete the picture of depositional environments we are attempting to reconstruct. Whether these interpretations meet with general acceptance or not, it is hoped that this report will direct increased attention to the still preplexing problems of the physical and chemical genesis of normal coal balls.

1. Some coal swamps were close to seashores and lay at or very near sea level, separated from the sea by a bar or barrier (White and Thiessen, 1913, p. 54). The coal beds containing mixed or faunal coal balls represent seaward parts of the swamps. The barrier between the sea and the swamp was low enough to be transgressed by unusual wave action.
2. Under episodically unusual circumstances the coal swamps were briefly invaded by sea waters and were contaminated with minor amounts of clastic marine material. Such invasions, although probably of very localized nature, occurred repeatedly in time and space, as shown by the geographic and stratigraphic distributions of mixed coal balls. They also were so brief that peat accumulation was not noticeably interrupted. The presence of mixed coal balls within the seams constitutes the only physical evidence for the marine invasions.
3. The American material described here introduces the probability that not all coal balls were formed under identical circumstances. Stopes and Watson (1908) suggested that coal balls developed by concretionary growth after marine invasion and cessation of peat deposition, the dissolved carbonates in the sea water percolating downward through the uncompressed peat and forming the matrix of coal balls. Since Stopes and Watson found no evidence of transitory marine inundations, their conclusions are sound insofar as their data are concerned.

   On the other hand, transitory marine ingressions could have had various effects on the swamp environment, which in turn may have stimulated concretionary growth of normal coal balls before final marine inundation. Waves and currents powerful enough to transport chunks of marine mud into the coal swamp would also have carried significant amounts of the mud in suspension, as well as carbonates in solution. Assuming that this mud was calcareous, it may have provided chemical material for concretionary calcification of some normal coal balls. The mechanism for reprecipitation of the carbonates remains speculatory at best, but subtle localized variations in pH may explain it as well as the sporadic occurrence of coal balls.
4. Coal balls may be concretionary, clastic, or both. Exclusively plant-containing, concretionary, and most probably autochthonous (normal) coal balls preponderate, but others contain marine animal remains and are interpreted as clastic allochthonous material (homogeneous-mixed and faunal coal balls); still others (heteregeneous-mixed coal balls) combine both types of contents and modes of origin.

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DETAILS OF SAMPLES AND INSOLUBLE RESIDUES

OSKALOOSA, IOWA

One coal ball (sample E–13) from the Patik mine was available. Parts of this specimen are illustrated on plate 31. figures 2 and 4. It is one of the more significant specimens studied in this research. Casual inspection of its sawn surfaces suggests an apparently normal coal ball with no conspicuous bedding or textural features. However, close examination reveals a few small gastropod shells scattered here and there. The predominantly cordaitean plant contents are very well preserved, even though pyrite is conspicuous in the matrix. The pyrite is partly oxidized, so that its dull luster renders it inconspicuous.

Residues of this sample are high in pyrite content, but abundant organic remains, mainly plant material with many coalified wood fragments and well-preserved pieces of cuticle of several types, were also recovered. The sample also contains the most diverse large-spore assemblage recovered in this study. This includes *Triletes* cf. *T. superbus*, *T. triangulatus* (pl. 33, figs. 21, 22), *T. auritus* var. *grandis*, *Spencerisporites* sp., *Monoletes ovatus*, and *Cystosporites* sp. Sample E–13 combines the widespread *Spencerisporites* type of spore with forms of *Triletes* that seem to characterize samples from other distinct areas but which rarely appear together in the same sample.

The fauna consists only of a few conodonts (pl. 34, fig. 45), pyritized ostracodes, and pyritized gastropods, which establish the presence of a marine element in this otherwise normal-appearing coal ball.

McALESTER, OKLA.

Several mixed coal balls from McAlester, Okla., were studied. In a few, the animal remains appeared to be locally concentrated in hazily defined bluish-gray parts of the matrix, which were lighter in color than the remainder and showed faint swirllike markings on sawn surfaces. Otherwise, these coal balls showed no distinctive textural features, and in most there was no obvious segregation of the animal remains.

Animal assemblages from this locality are mostly dominated by well-preserved pyritized ostracodes. Pelecypods and gastropods are fairly common; conodonts, fish remains, and other animal groups are only sparsely represented. The following samples were dissolved:

E–11.—Organic contents of the residue are largely of plant origin. Most of the plant fragments are small, and their parallel ribbing and stomata arranged in rows parallel to the ribs indicates they are coalified cordaitean leaf fragments. Fusinized wood fragments and cuticular remnants are also common, but very few spores were found. Most of the spore material consists of incomplete but uncompressed fragments of the *Triletes auritus* type; one small lageniculate specimen of *Triletes* (cf. *T. rugosus*) was also found.

With the exception of conodonts and fish remains, the animal fossils are all preserved as pyritic replacements. Poorly preserved Ostracodes are most common, small pelecypods are relatively abundant, worm tubes (pl. 34, fig. 46), gastropods, and fish fragments are rare, and one bryozoan was found.

E–22.—This coal ball was similar to E–11, although slightly less pyritized. Almost the same plant material is present in the residue; several specimens of a lageniculate species of *Triletes* (cf. *T. rugosus*) were recovered (pl. 33, figs. 18, 19).

Among the animal remains, ostracodes are again the dominant element, with gastropods (pl. 34, fig. 31) and pelecypods (pl. 34, fig. 27) also common. A few bryozoans, conodonts (pl. 34, figs. 42, 43), scolecodonts (pl. 34, fig. 35), inarticulate brachiopods (pl. 34, figs. 17, 18), and fish fragments (pl. 34, figs. 52–57) were found, along with attached and free-living foraminifers. Some coprolites also occur (pl. 34, figs. 33, 34), as do worm tubes (pl. 34, figs. 38, 46).

E–30.—This small normal coal ball appeared to contain moderately well preserved plant material, but the residue yielded only a few spores, cuticles, and pyrite-filled woody fragments. The spores include a few specimens of *Triletes* cf. *T. rugosus*, two questionable fragments of *T. auritus*, and one specimen of *Monoletes ovatus*.

No animal remains are present in the residue.

E–31.—This is a large irregularly shaped homogeneous-mixed coal ball, a foot long and nearly as broad. Several stringers of coal extend inward 1 to 2 inches from the periphery of the coal ball, whose content appears on sawn surfaces, to be poorly preserved plant material. Bedding was not detected in the specimen.

Animal remains are inconspicuous on sawn surfaces and are not concentrated at any spot. The fauna in the residue is primarily moluskan, with several genera of pelecypods and gastropods, the former being the more abundant (pl. 34, figs. 22, 28). One species of cephalopod also occurs (pl. 34, fig. 29). The remainder of the fauna consists of a few fish fragments, inarticulate brachiopods, foraminifers (pl. 34, figs. 3, 8), some ostracodes, and a relatively large number of worm tubes.

Plant material is represented by many coalified wood fragments and a few cuticular scraps and spores. The latter consist of approximately equal numbers of *Triletes* cf. *T. rugosus* and *T. auritus* var. *grandis*. One specimen of *Cystosporites varius* was also found.

E–16.—Associated with the Secor coal, and presumably above it, is a fossiliferous limestone. A sample was dissolved to ascertain whether any relation exists between the fauna of the mixed coal balls and that of the limestone caprock.

Animal remains in this sample are all pyritized and too poorly preserved for generic or specific identification. The fauna shows less diversity than those of the associated mixed coal balls. It contains a few specimens of three genera of pelecypods, one genus of gastropods, some inarticulate brachiopod fragments, foraminifers, and fish parts.

Plant material consists only of small fragments of fusinized wood and a few resin rodlets.

SOUTHEASTERN KANSAS

WEST MINERAL—PITTSBURGH AND MIDWAY COAL CO. PITS

A large number of homogeneous-mixed coal balls from West Mineral, Kans., were examined. Some show rather well defined swirled textures, particularly the few that contain larger brachiopods. A few others show local concentrations of animals surrounded by fairly pure plant material.

The West Mineral specimens contain more pyrite and other insolubles than those from any other locality, with the exception of the Apex-Compton mine near Monmouth. (See table 2.) However, a few of the West Mineral coal balls approach the latter in degree of pyritization.

Biologically, the West Mineral material is the richest examined thus far, both for variety and size of fossils. It contains *Marginifera* and small specimens of *Derbyia*. Animal remains as large as these have not been found in mixed coal balls from any of the other localities.

Aside from the large brachiopods, most of the faunal contents are small unbroken individuals, either mature or preserved in younger growth stages. A few small (2 mm and less in diameter) brachiopods and pelecypods were found, with ornamentation and delicate spines undamaged.

E–9.—This large coal ball lacks any distinctive textural features and contains relatively few animals, scattered throughout the matrix. Although a few larger brachiopods and 2 cephalopods are evident on the sawn and broken surfaces, the acid residues contain a sparse fauna that consists only of 6 specimens of gastropods, one pelecypod, and several conodonts and poorly preserved ostracodes.

Recovery of plant material was poor, but a fairly large number of uncompressed spores are present in the residues. These contain *Spencerisporites* sp., *Triletes* cf. *T. superbus*, and *T. triangulatus*.

E–10.—This is a small, heavily pyritized coal ball that appears normal except for a few gastropods evident on cut surfaces. The faunal content of acid residues consisted only of four small gastropods. The plant material contains many fusinized wood slivers, a few resin rodlets, and some cuticular material. Numerous spores were recovered, chiefly large specimens that appear to represent spores of *Triletes* cf. *T. superbus* in which the large equatorial frill has been accidentally separated from the spore body; one specimen of *Spencerisporites* sp. was also found.

E–12.—Many animal fragments, including larger brachiopods, are visible on sawn surfaces of this specimen, and are scattered throughout the matrix. Although few of these were recovered in the acid residues, they embrace a variety of zoological groups. Several larger brachiopods and fragments of inarticulate brachiopods, a few pelecypods and gastropods, fish scales and teeth, ostracodes and adherent foraminiferal tests make up the fauna.

A varied spore population dominates the plant material. Most conspicuous are *Triletes* cf. *T. superbus* and *Spencerisporites* sp.; *T. triangulatus, Monoletes ovatus*, and *T. auritus* constitute a slightly less conspicuous fraction of the spore assemblage.

E–18.—This specimen was selected as a representative normal coal ball. Careful inspection of its sawn surfaces showed no animal fossils, and their absence was corroborated by the acid residue.

Abundant plant cuticles and spores were recovered. *Triletes* cf. *T. superbus*, so conspicuous in mixed coal ball specimens, is lacking in this sample. However, *T. triangulatus*, *Spencerisporites* sp., and *Monoletes ovatus* are present, and establish a common element with the mixed coal balls.

E–23.—This large unlayered coal ball contained numerous animals, homogeneously scattered among the plant remains throughout the matrix. Faunally, it proved to be one of our richest specimens. Acid residues yielded numerous pelecypods, gastropods, and larger brachiopods (pl. 34, figs. 19, 20), two specimens of cephalopods, rare ostracodes, fish remains, conodonts, one scolecodont, abundant worm castings, a spongelike object, and many adherent forminiferal tests of the *Serpulopsis* type. The latter are also attached to associated fossils, both plant (pl. 33, figs. 25–30) and animal.

Plant remains in the residue contain abundant fusinized wood fragments, cuticular material, one coalified lycopodiaceous branch tip with intact leaves (pl. 33, fig. 32), intact masses of small spores, resin rodlets, and numerous large uncompressed spores. The latter are dominated by *Triletes* cf. *T. superbus*, which, with its ornate equatorial frill and trilete appendages presents a striking appearance in its fully distended, natural shape (pl. 33, figs. 5–7). Some specimens of this species have pyritic fillings (pl. 33, fig. 9), while the empty interiors of still others indicate the calcitic nature of their former fillings. Many specimens of this species were found with *Serpulopsis* tests adherent, both internally on broken fragments (pl. 33, fig. 28) and externally on intact specimens (pl. 33, figs. 27, 29, 30).

Other spores present in this sample are *T. triangulatus*, *Spencerisporites* sp., and *Monoletes ovatus*.

E–24.—This small coal ball yielded few animal remains with the exception of abundant foraminiferal tests of the *Serpulopsis* type. The few pelecypods recovered are diversified generically. A few spores of *Triletes* cf. *T. superbus* and *T. triangulatus* were recovered; these represent the total of recognizable plant material.

E–14. (Limestone overlying Mineral Coal).—Residues of this sample contain, in addition to pyrite, an abundance of small flakes of silty material, which is not present in significant amounts in any of the coal ball specimens.

Recovery of fossils was low. The animals consist mostly of ostracodes and broken undetermined brachiopod spines. Plant material, also scarce, consists of rare cuticle fragments, slivers of fusinized wood, compressed and poorly preserved *Triletes*-type megaspores, and two uncompressed specimens of *Spencerisporites* sp. The latter provide the single common botanical element with the coal ball residues.

MONMOUTH—APEX-COMPTON COAL CO. PITS

The area of the Bevier coal seam now being mined by the Apex-Compton Co. is unusual in that its abundant nodular impurities, which we consider to be coal balls, are extremely pyritic and composed almost exclusively of animal fragments. In the many coal ball samples examined, plant remains are nearly or completely absent, while the closest approaches to normal coal ball samples yielded only fragments of fusinized wood.

Some of the mixed coal balls show homogeneous texture and are heavily pyritized throughout. In others, however, the matrix is differentiated into a fairly distinct central nucleus of nearly pure pyrite in which all fossils have been completely obliterated, surrounded by areas of less complete pyritization in which fossils may be recognized. A few specimens contain roughly concentric zones of varying concentrations of pyrite.

Four samples were dissolved, including one that seemed to be a normal but poor quality coal ball.

E–7.—The specimen is a slightly flattened nodule with adherent coal chips on all surfaces and streaks of coal incorporated within the matrix. It contains a clearly defined, nearly central area of almost solid pyrite that is surrounded by a less heavily pyritized zone in which animal fossils are abundant. A few calcareous crinoid columnals are apparent on sawn surfaces, but most of the animal remains are pyritized brachiopods and gastropods.

The residue is estimated to contain 90 to 95 percent pyrite, most of which consists of finely comminuted animal shell fragments that apparently originated from productoid brachiopods and large bellerophontid gastropods; the pyrite is relatively lustrous and unoxidized. The residue also produced a number of complete small generically diversified gastropods (pl. 34, figs. 25, 26), some poorly preserved ostracodes, foraminiferal tests, conodonts, and fish remains.

Except for very rare and small fusinized wood particles, plant remains are absent from this sample.

E–8.—This specimen is similar to E–7, but less pyritized. The residue consists mostly of small fragments of invertebrate shells. The determinable faunal content is similar to that of E–7, except for the absence of foraminiferal remains.

No plant remains were observed in the residue.

E–20.—This specimen has adherent coal on all surfaces and coaly inclusions within the matrix. Sawn surfaces contain a definite, almost centrally located mass containing well-preserved baritic fossils. This area is surrounded by a zone of heavy pyritization in which the animal remains are also pyritized, and there is a clear contact between the two zones. Local areas of the outer zone are so heavily pyritized that the fossils are practically obliterated.

A part of the inner zone was dissolved, and it produced a small amount of residue. The faunal content of the residue contained abundant baritic gastropods (pl. 34, figs. 23, 30), rare baritic pelecypod fragments, a few conodonts, and fish remains.

The plant remains consisted only of small fusinized wood particles and a sparse spore assemblage, which includes *Monoletes ovatus* and *Triletes* cf. *T. auritus.*

E–21.—This is a small ellipsoidal, apparently normal coal ball, with only poorly preserved cordaitean wood fragments apparent on sawn surfaces. Acid solution produced only woody splinters, highly impregnated with pyrite. No spores or animal remains were noted.

FRANKLIN—MACKIE-CLEMENTS FUEL CO. MINE NO. 23

Normal coal balls from this locality cannot be distinguished from those of the Pittsburgh and Midway mine on the basis of plant contents or overall appearances. This fact would seem to lend weight to local miners' opinions that the same coal seam is being mined at the two sites. (See p. 201.)

The mixed coal ball specimens are variable in pyrite content, and the pyrite may be more concentrated in one part of the nodule than another. None, however, are as heavily pyritized as the Monmouth specimens.

The fauna included in the mixed specimens is fairly varied, but apparently dominated by the brachiopod *Mesolobus*, invariably replaced by pyrite. Calcareous crinoid columnals are abundant on sawn surfaces; they occur even in the most heavily pryitized parts of the nodules; these, of course, are lost in the acid treatment. Ostracodes, chonetid brachiopod spines, and worm castings are also common, and there are a few other faunal elements, as noted below.

Plant material is very rare in residues of mixed specimens from this locality.

E–1.—The sample does not appear to be heavily pyritized, nor does it show outstanding textural features. The residue is approximately 90 percent pyrite, but this includes no large masses such as characterize residues of the Monmouth specimens; the pyrite is relatively lustrous.

The larger animal fragments are apparently of *Mesolobus* (pl. 34, fig. 21) and larger productoid origin, while the finer screen sizes of the residue consist of perhaps 50 percent brachiopod spine fragments. In addition to the brachiopods, several crinoid columnals, foraminiferal tests, rare ostracodes (pl. 34, figs. 47, 51), conodonts, and fish fragments were found.

Plant material consists mostly of small fragments of fusinized wood; cuticular material is very rare, and spores were not noted.

E–2.—This sample has a swirled texture and is more pyritized than E–1; recovery of fossils was poor. Pyritization is especially localized in one eccentrically located area. The pyrite constitutes approximately 95 percent of the residue and lacks luster. The most abundant animal fossils recovered were fragments of *Mesolobus*. In addition, a few crinoid columnals, several gastropods, poorly preserved ostracodes, conodonts, and fish remains were noted.

Plant material is rare; it consists largely of small fragments of fusinized wood and a few reesin rodlets. No spores or cuticular material were found.

E–17.—This is a normal coal ball, with vague horizontal layering. Parts of the specimen contain large pieces of cordaitean wood, but many well-perserved smaller plant structures are evident on sawn surfaces (principally *Cordaicarpus*, *Stigmaria*, and *Scolecopteris*). However, surprisingly few identifiable fragments survived acid solution. The residue of this sample, which contains very little pyrite, yielded only fusinized wood particles, cuticular fragments, and a few spores, which contain *Spencerisporites* sp., *Monoletes ovatus*, and one tetrad of *Triletes triangulatus.*

No animal remains were found in this sample.

BERRYVILLE, ILL.

Mixed coal balls from this locality are unique in several respects, the most striking of these being the clearly defined cores of marine sediment incorporated within the otherwise normal type of coal ball matrix (pl. 30, fig. 1–3; pl. 31, fig. 1). They are further unique in their high proportion of acid-soluble carbonates. None of the Berryville coal ball samples contained as much as 6 percent insoluble matter, whereas samples from other localities contained from 6.1 to 36 percent.

From the zoological standpoint, Berryville material is distinct in that its fauna is dominated by pyritized bryozoans, a group that is nearly absent from all other samples. Furthermore it contains pyritized trilobite fragments, which are unique in coal balls from this locality. Siliceous foraminiferal tests and crinoid columnals are also much more conspicuous here than elsewhere. The residues also contain coalified wood, cuticles, and many well-preserved spores.

The marine cores of mixed coal balls also seem to be low in pyrite content, and their sawn surfaces show many calcified crinoid remains. The residues contain 50 to 60 percent pyrite, but this is either in the form of a fine powder or animal replacements; it rarely appears in large amorphous masses like those contained in residues from other localities.

In view of the unusual nature of Berryville coal balls, a large suite of samples was dissolved. This suite includes: (a) core material from which all normal matrix had been carefully trimmed; (b) samples of normal matrix surrounding the core; (c) samples of a normal coal ball; (d) samples of limestone incorporated within the coal seam; and (e) samples of the limestone overburden.

E–3.—This specimen was taken from a long cylindroidal core containing several conspicuous calcite-filled shrinkage(?) cracks. Its cut surface showed many crinoid columnals and tubular foraminiferal tests. The residue is small (2.9 percent of the total weight), but contains a varied assemblage. Animals include conodonts, pelecypods, gastropods, rare brachiopods, fish fragments, common foraminiferal tests, a few trilobites, and abundant bryozoans.

Abundant plant material is present, including fusinized wood and cuticular fragments, in addition to a varied spore assemblage. Spores include *Triletes auritus* var. *grandis*, *T. triangulatus*, *T. glabratus*, *Spencerisporites* sp., *Monoletes ovatus* (the most abundant form—see pl. 33, figs. 1, 2), and a few specimens of *Parasporites* cf. *P. maccabei* (pl. 33, figs. 23, 24). Small trilete spores are abundant in the finest residues, but there were not identified.

E–4.—This sample resembles E–3, but its insoluble residue is smaller and contains less pyrite.

The fauna is nearly the same as that of E–3, except that foraminiferal tests are more conspicuous here. A plant assemblage similar to E–3 and differing only in the absence from E–4 of the *Parasporites* is also present.

E–19.—This is a normal coal ball with distinct layering of its abundant and well-preserved plant debris evident on sawn surfaces. It was selected for solution in order to determine (a) whether animal fossils are actually absent, as suggested by inspection of sawn surfaces, and (b) what comparisons could be made between its plant content and that of the marine cores.

Little residue was obtained (4.6 percent), and this contains almost no pyrite. The residue, all of plant origin, has the appearance of a chaffy light- to dark-brown mass of more or less finely divided fragments of cuticles and wood, complete spores, and various other reproductive parts. No animal remains were found. Spores are rare; only a few masses of small trilete spores, two specimens of *Monoletes ovatus*, and one of *Spencerisporites* sp. were found. Surprisingly enough, *Triletes auritus* was not found in this sample.

This residue is, however, of unusual interest in that it contains several uncompressed and otherwise undamaged specimens of a species of small pteridospermous seeds, and numerous scolecopterid fern fructifications. The seeds are hollow as a result of solution of their calcitic fillings, and are represented by a delicate inflated membrane that probably is the inner layer of the testa (endotesta). Cellular outlines may easily be seen with a dissecting microscope. Although the seeds cannot be identified without a knowledge of their inner structural details, overall size and shapes suggest affinity with the genus *Coronostoma* Neeley, which has been described from Berryville coal ball material; at any rate, they are unquestionably conostomalean structures (pl. 33, fig. 31).

The fern fructifications consist of uncompressed synangia that were apparently preserved after maturity and dehiscence (pl. 33, figs. 33–36). The synangia are evidently referable to *Scolecopteris minor*, and contain four or five sporangia each, the sporangia being 1 mm. or less in length. Many of the synangia have their pedicels intact, and a few specimens of fertile pecopterid pinnules have been found. Furthermore, one very delicate circinate pecopterid frond tip with several pinnules attached was found.

Although these recoveries have little bearing on the basic problem under consideration, they demonstrate that studies of coal ball plant fossils based on the peel technique might well be supplemented to great advantage by acid solution in order more accurately to understand the three-dimensional aspects of the plant fossils investigated.

E–25.—The residue of this core sample contains one of the most varied faunas found in this study. Animal remains include trilobite fragments, poorly preserved brachiopods, abundant and diversified gastropods (pl. 34, fig. 32), worm tubes and castings, some pelecypods, conodonts (pl. 34, fig. 36), abundant ostracodes, foraminiferal tests, bryozoans (pl. 34, figs. 11, 13–16), a few fish fragments, and several sponge spicules (pl. 34, figs. 9, 10).

The usual fusinized wood and cuticular fragments also occur, along with well-preserved uncompressed spores, the most abundant form being *Triletes auritus* var. *grandis*. *Monoletes ovatus*, *Spencerisporites* sp., and *Triletes glabratus* complete the spore assemblage.

E–26.—This core was physically similar to E–25. Its fauna differs from the former only in a larger representation of trilobite remains (pl. 34, figs. 39–41), and the spore assemblage contains a higher percentage of *Triletes glabratus* (pl. 34, figs. 3, 4), although *T. auritus* var. *grandis* still dominates (pl. 34, figs. 15–17). Part of this specimen is illustrated on plate 30, figure 2.

E–27.—This coal ball contains a very sharp contact delimiting its cylindroid core, and two samples, one consisting of carefully trimmed core material and the other of the surrounding normal matrix, were dissolved to compare the differences in content between the core and normal matrix surrounding it. Part of this specimen is illustrated on plate 30, figure 3.

The fauna recovered from the residue of the core is typical of the Berryville material, except that neither ostracodes nor conodonts are evident, and a few pyritized crinoid columnals were recovered. Plant material is rare in this sample, the most conspicuous elements being a few specimens each of *Triletes auritus* var. *grandis*, *T. glabratus*, and *Spencerisporites* sp.

The residue of the normal matrix surrounding the core contains no animal remains and little pyrite. It consists only of plant debris, mostly brown and peaty-appearing. The residue contains a few scolecopterid fern synangia, well-preserved cuticles, abundant fusinized wood fragments, and only a few spores, identified as *Triletes triangulatus*, *Spencerisporites* sp., and *Monoletes ovatus*.

E–28.—Two samples of this mixed coal ball were treated as in E–27. The core residue yielded a varied fauna, unusual only in the apparent absence of conodonts. Plant debris is scarce; it consists of the usual cuticles, fusinized wood fragments, and spores, the latter being represented by *Triletes auritus* var. *grandis* (the dominant form), *T. glabratus*, and *Spencerisporites* sp. (pl. 33, figs. 11–14).

Residue of the normal matrix surrounding the core contains no animal remains and almost no pyrite. Cuticles, fusinized wood fragments, and spores are abundant, but *Spencerisporites* sp. is the only spore type recovered from this residue.

E–29.—This core sample yielded a varied fauna, including trilobites, foraminiferal tests (pl. 34 figs. 4, 8), hexactinellid sponge spicules, worm tubes and castings, fish fragments, conodonts (pl. 34, fig. 44), articulate and inarticulate brachiopods, bryozoans, ostracodes (pl. 34, figs. 48–50), and diversified mollusks.

The usual type of plant debris is present in the residue, and it contains one of the most varied and richest spore assemblages found. This assemblage is dominated by *Triletes auritus* var. *grandis*, but it also contains *T. glabratus*, *T.* cf. *T. rugosus*, *T. triangulatus*, *Cystosporites varius*, *Spencerisporites* sp., and *Monoletes ovatus*.

E–6.—This sample of the limestone overlying the coal seam (unit 3 of measured section, p. 198) proved to be nearly pure carbonate, with its insoluble fraction constituting only 0.42 percent of the original weight. Sawn surfaces are similar to those of the cores, being bioclastic crinoidal limestone. However, this rock has a significantly coarser and less well sorted texture, with many of the crinoid stems two to three times as large as those in the cores.

The faunal content of the sample consists only of a few conodonts, fish remains, tubular foraminiferal tests, and one specimen each of a scolecodont, a gastropod, and pelecypod. The gastropod steinkern, though not tested, appeared to be phosphatic. No pyrite is evident in the residue; plant material is absent.

E–5.—A sample of the limestone filling of the presumed channel cut in the coal seam was more fossiliferous than the overlying limestone (E–6); its residue contains a large proportion of pyrite. In texture and faunal content this rock is very similar to the cores.

Animal remains recovered from the residue include abundant bryozoans, relatively few pelecypods, and worm castings, sparse ostracodes, rare gastropods and brachiopods, and some trilobites and conodonts; all but the worm castings and conodonts are pyritized.

Plant material is sparse, with some cuticle and woody material and a few well-preserved spores. The latter include *Triletes auritus* var. *grandis* (the dominant form), *T. glabratus*, *Spencerisporites* sp. and an unknown spore that, except for its large size, is similar to *Lycospora* in form.

E–15.—This is a sample of the impure limestone below the channel as discussed on page 198. This material is illustrated in plate 31, figures 3, 5, and 6.

The acid residues contain no animal remains. The plant debris is mostly small and unrecognizable flakes of incompletely coalified plant material. However, abundant well-preserved cuticular material and uncompressed spores were recovered. The spores include *Triletes auritus* var. *grandis* (the dominant form), *Spencerisporites* sp., *Triletes glabratus*, and one specimen of *Parasporites* cf. *P. maccabei.*

INDEX

PLATES 26–34

PLATE 26

FIGURE 1. Closeup of channeling in coal bed at Berryville, Ill. Several coal balls may be seen to the right of and below the hammer.

2. A large coal ball mass overlying 4 inches of coal at Berryville, Ill. Part of this mass may be seen in the lower left corner of figure 3.

3. General view of the Berryville, Ill., locality. The channel and swelling of the overlying limestone is shown at left center of photograph, above stream level. Section was measured along trench at right of photograph.

4. A part of one of the piles of coal balls near the tipple of the Pittsburg and Midway Coal Co., West Mineral, Kans.

5. View of Bevier coal in Apex-Compton Coal Co. strip pit near Monmouth, Kans., showing two faunal coal balls in place, (at arrows), overlain by more than an inch of coal. Irregularly shaped coal ball directly above light meter, with tabular specimen to left. Flat specimen also shown in figure 6; sawn surfaces of both specimens shown in plate **32**. Photograph by R. W. Baxter, University of Kansas.

6. View of Bevier coal taken a few minutes prior to figure 5, showing the flat faunal coal ball when first exposed. Arrow to left of light meter points to upper surface of coal seam; tabular coal ball below and to right of arrow. Photograph by R. W. Baxter, University of Kansas.

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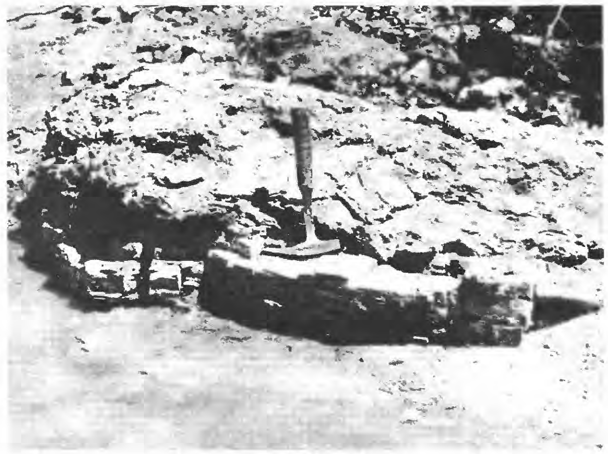

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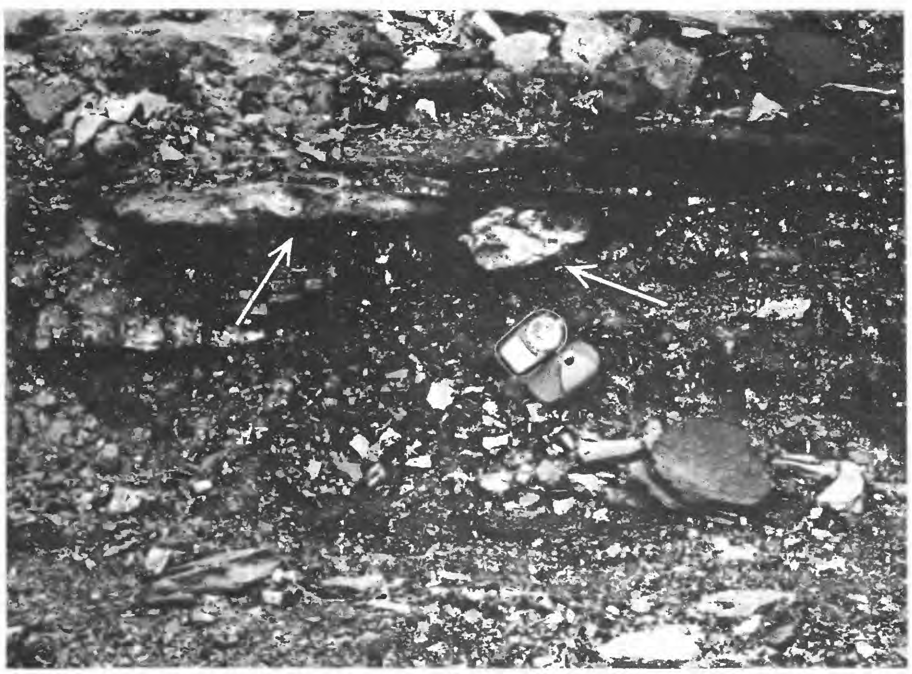

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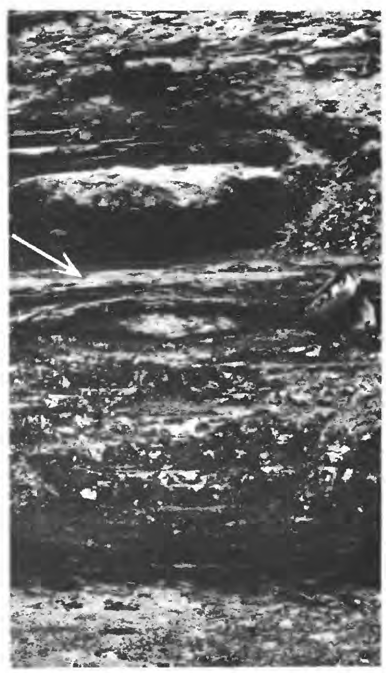


6

VIEWS AT THE BERRYVILLE, ILLINOIS, WEST MINERAL, KANSAS, AND MONMOUTH, KANSAS, COAL BALL LOCALITIES

PLATE 27

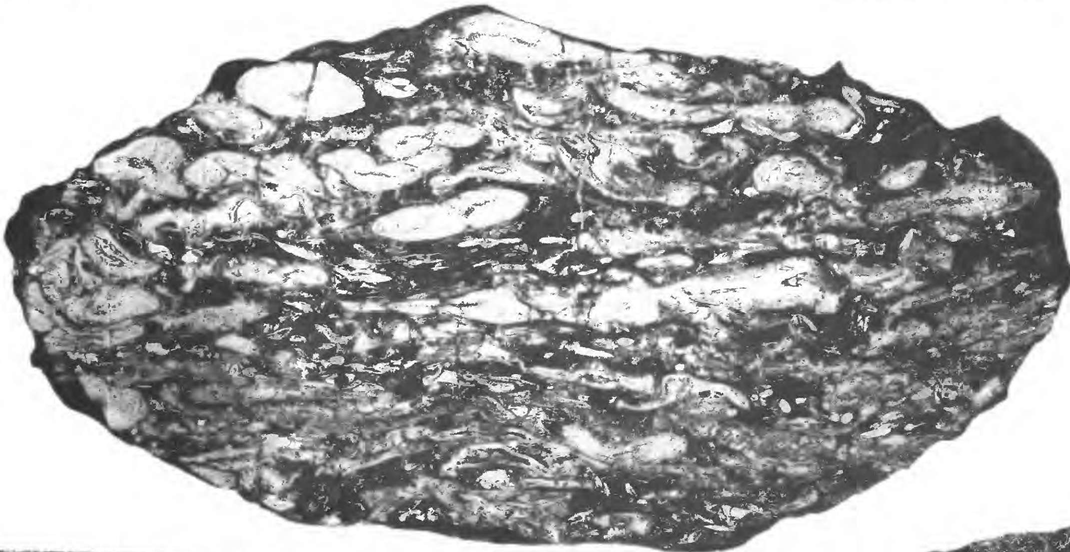
[Photographs natural size unless otherwise shown]

FIGURE 1. Sawn surface of a normal coal ball from Berryville, Ill., showing layered appearance of plant debris, primarily fern roots. Specimen 9190–31C.

2. Enlargement of part of specimen illustrated in figure 3, showing cross section of high-spired gastropod. $\times$ 3.

3. Sawn surface of small homogeneous-mixed coal ball from West Mineral, Kans., containing primarily plant debris, with gastropods scattered at random through the ball. Enlarged area indicated by arrow. Specimen 9189–123A.

4. Sawn surface of homogeneous-mixed coal ball from West Mineral, Kans., showing well-defined swirled texture and, locally, alinement of shell fragments parallel to swirls. The fossils are predominantly animal, but a large stigmarian stele is shown at left center of photograph. Specimen 9189–121C.



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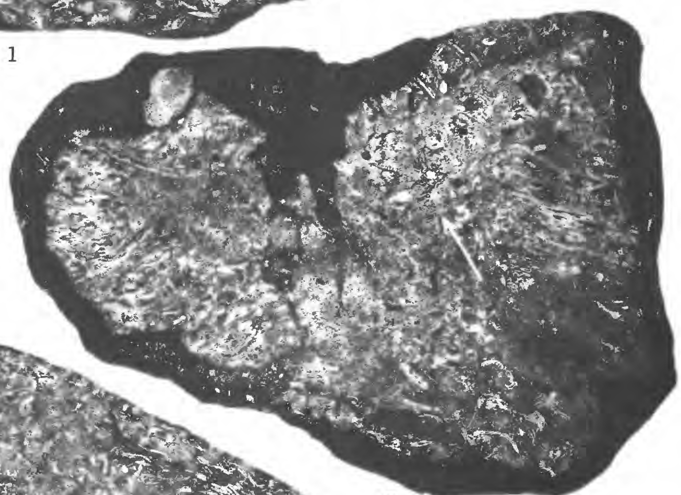

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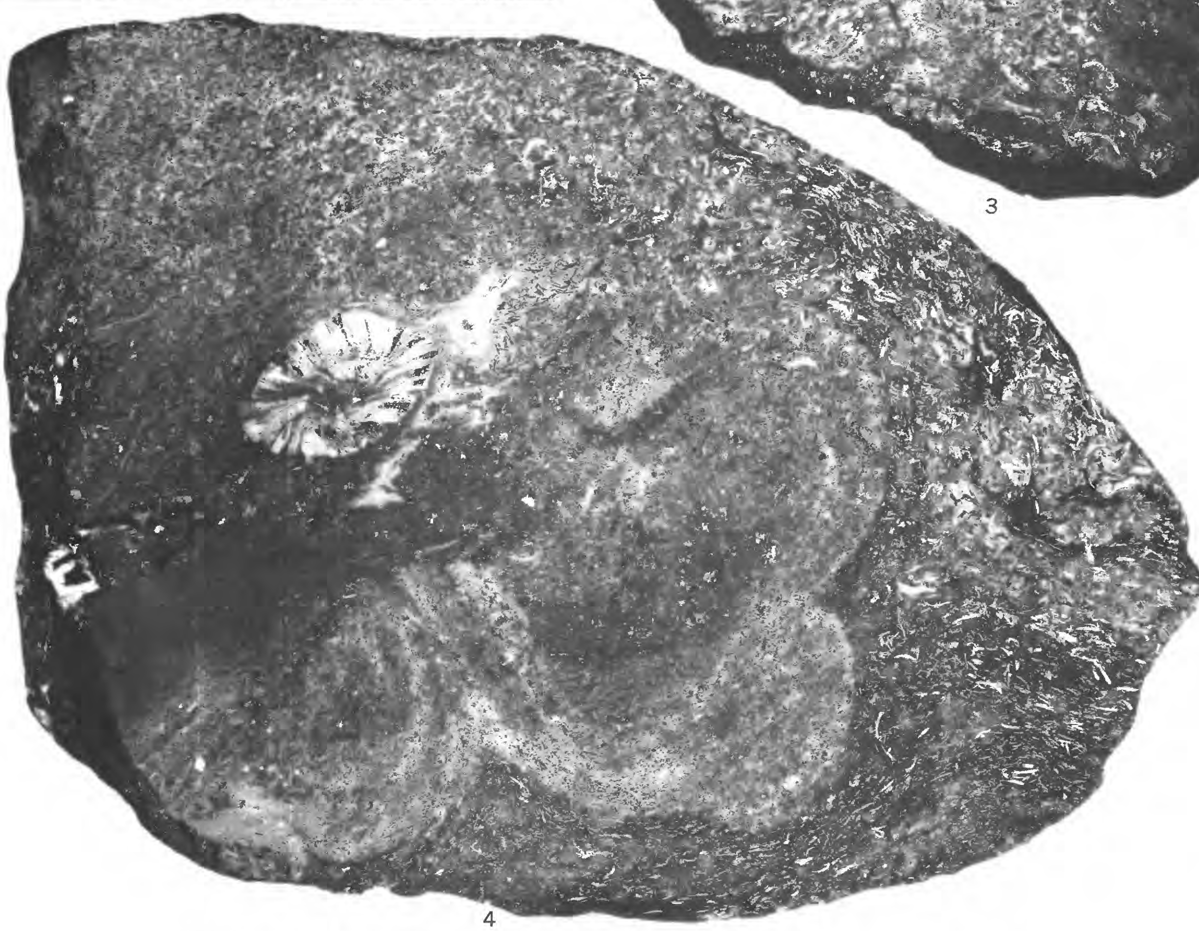


4

NORMAL AND MIXED COAL BALLS FROM ILLINOIS AND KANSAS

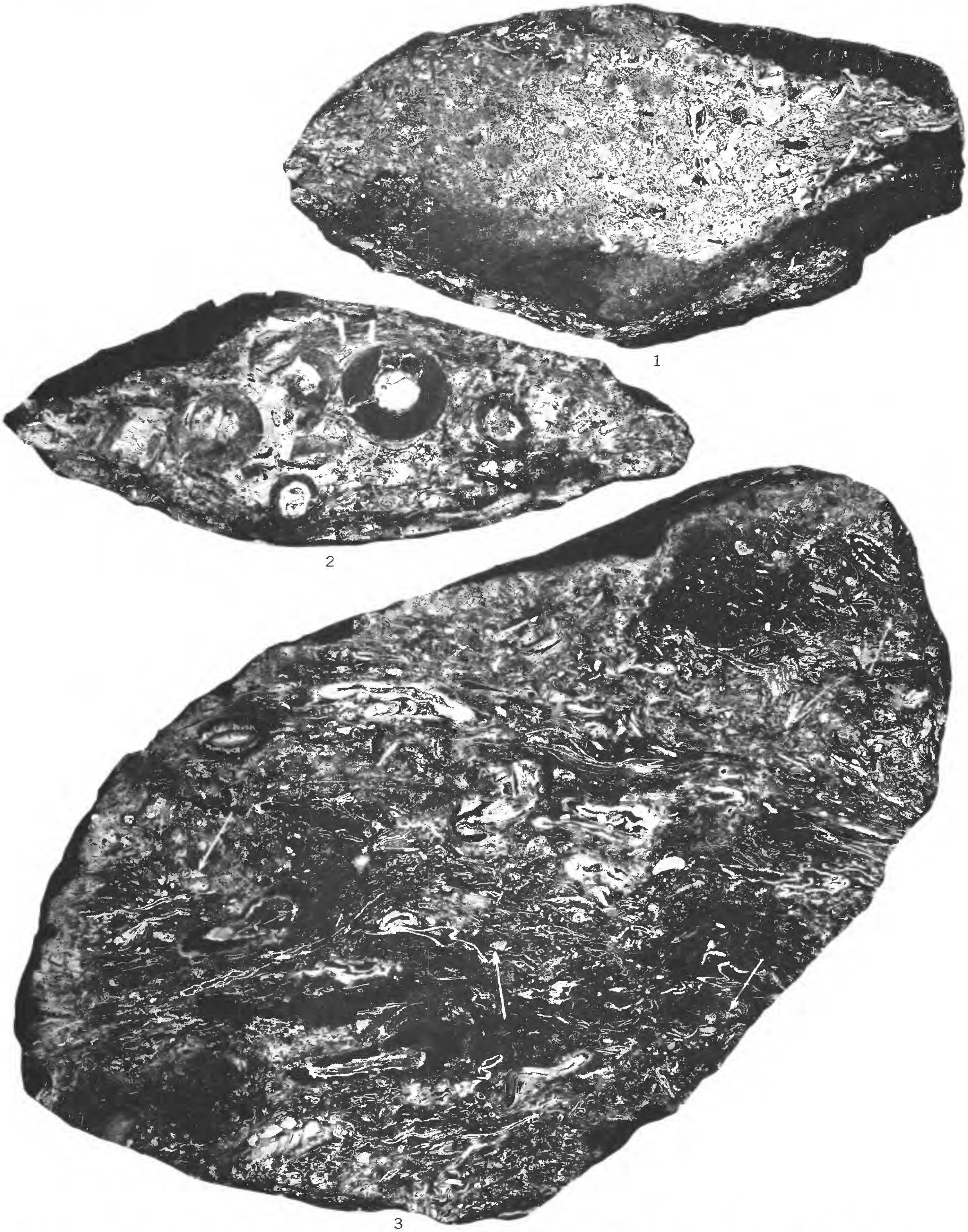
PLATE 28

[Photographs natural size]

FIGURE 1. Sawn surface of faunal coal ball from near Monmouth, Kans., showing lenticular shape and abundant pyritized animal debris. Specimen 9487-1A.

2. Sawn surface of normal coal ball from West Mineral, Kans., showing lenticular shape. Plant debris consists predominately of cordaitean leaves, stems, and fructifications. Specimen 9189–80D.

3. Sawn surface of homogeneous-mixed coal ball from West Mineral, Kans. Organic content predominately plant debris that includes well-preserved cordaitean organs. Some marine gastropod shells indicated by arrows. Specimen 9189–120C.



FAUNAL, MIXED, AND NORMAL COAL BALLS FROM WEST MINERAL AND MONMOUTH, KANSAS

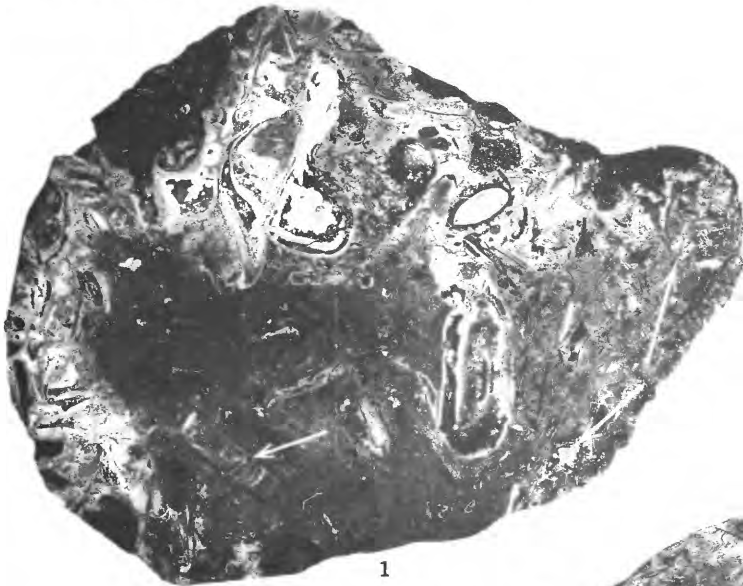
PLATE 29

[Photographs natural size unless otherwise shown]

FIGURE 1. Sawn surface of homogeneous-mixed coal ball from West Mineral, Kans.; coal ball composed predominately of plant material that includes well-preserved cordaitean seeds. Orthoceroid cephalopod and gastropods indicated by arrows. Specimen 9189–122A.

2. Enlargement of part of specimen illustrated in figure 3, showing associated plant and animal remains. Cross section of a gastropod shell and a pteridophyllous pinnule indicated by arrows. × 4.

3. Sawn surface of a homogeneous-mixed coal ball from West Mineral, Kans., showing mixture of plants and animal remains. Specimen 9189–124C.



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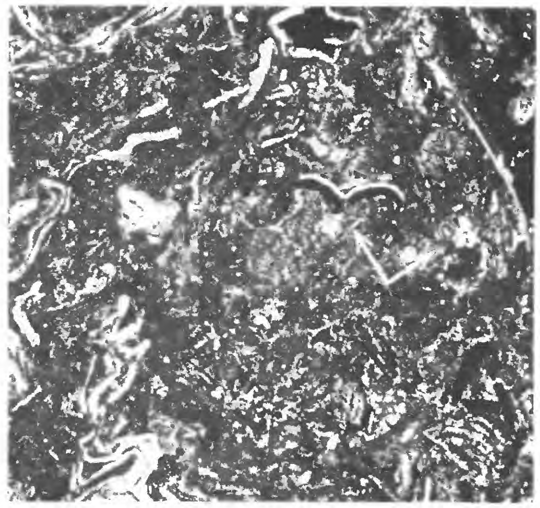

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3

HOMOGENEOUS-MIXED COAL BALLS FROM WEST MINERAL, KANSAS

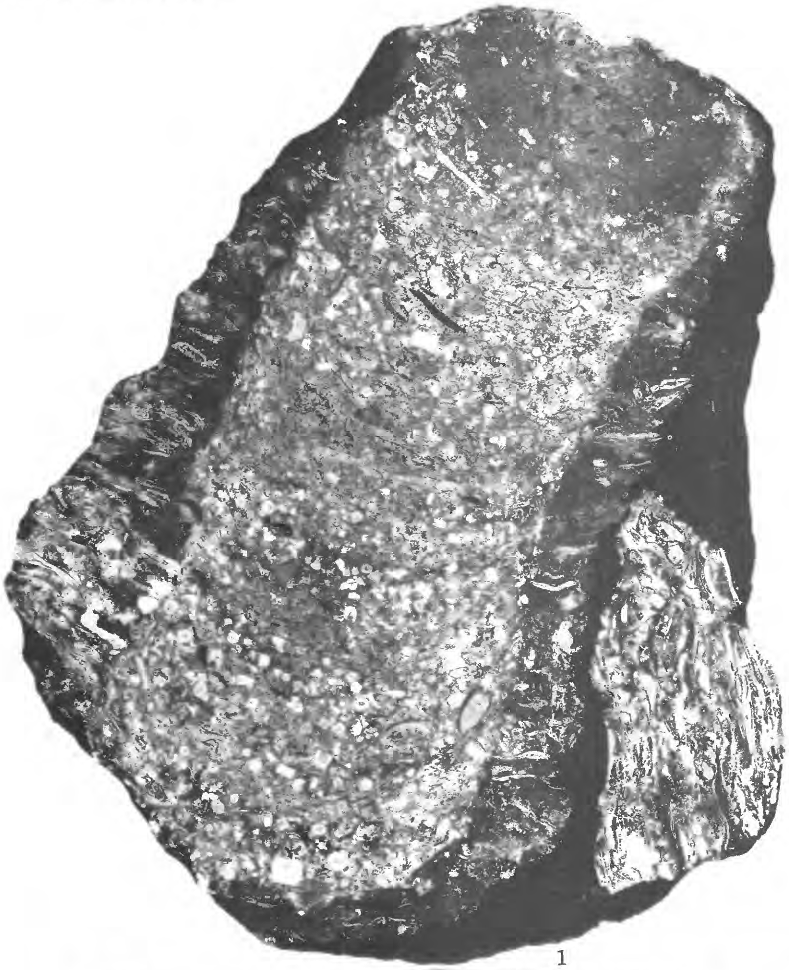
PLATE 30

[Photographs natural size]

FIGURE 1. Sawn surface of a heterogeneous-mixed coal ball from Berryville, Ill., showing stratification of marine fossil fragments within the large marine core. A small normal coal ball lies to the right of the photograph. The layering of plant debris in the normal coal ball and the normal part of the mixed coal ball are approximately at right angles to one another. Specimen 9190–1E.

2. Sawn surface of a heterogeneous-mixed coal ball from Berryville, Ill. The layering of the normal part is at right angles to the bottom of the plate. Specimen 9190–13E. Part of this specimen was dissolved as sample E–26.

3. Sawn surface of a heterogeneous-mixed coal ball from Berryville, Ill., showing an irregular marine core. The black line above the core is a coal film. Specimen 9190–17D. Part of this specimen was dissolved as sample E–27.



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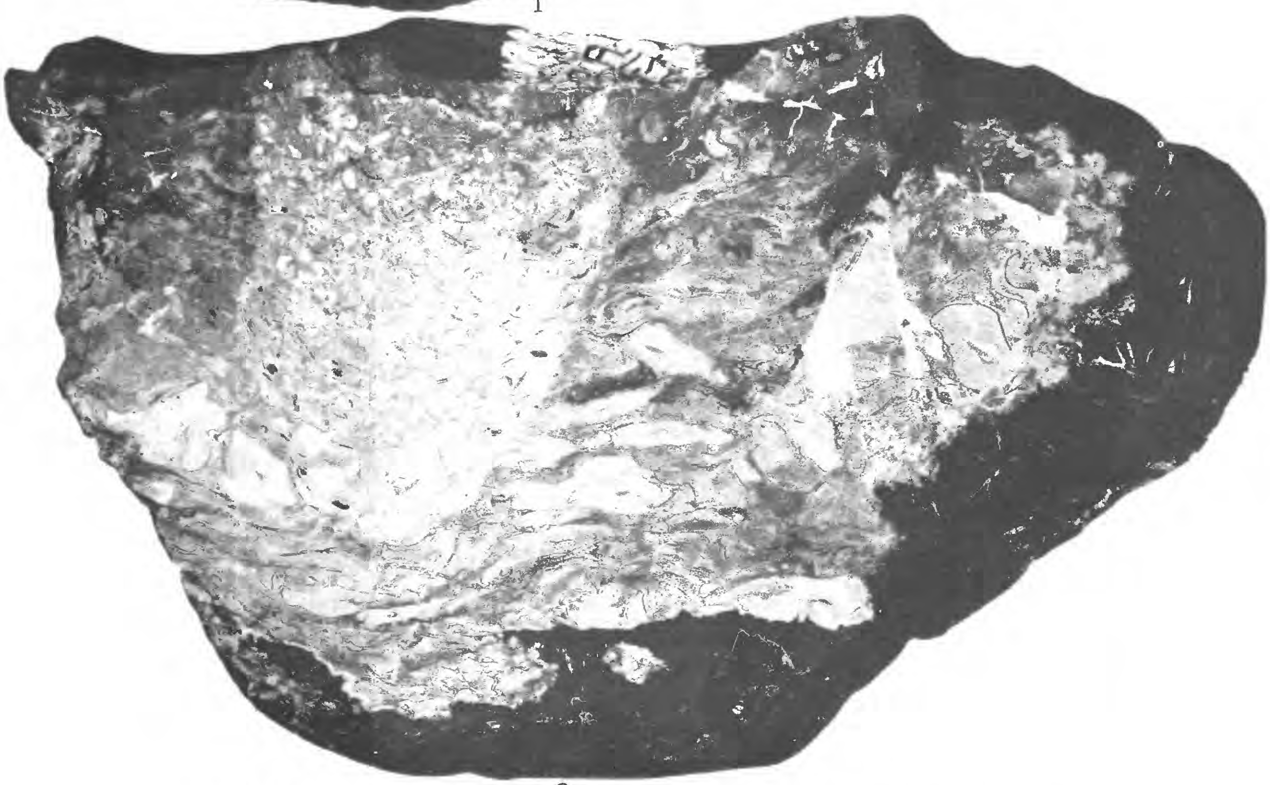


3

HETEROGENEOUS-MIXED COAL BALLS FROM BERRYVILLE, ILLINOIS

PLATE 31

[Photographs natural size unless otherwise shown]

FIGURE 1. Sawn surface of heterogeneous-mixed coal ball from Berryville, Ill., showing discrete nature of core of marine material with abundant animal debris, and complete enclosure of core within normal coal ball material. Specimen 9190–2F.

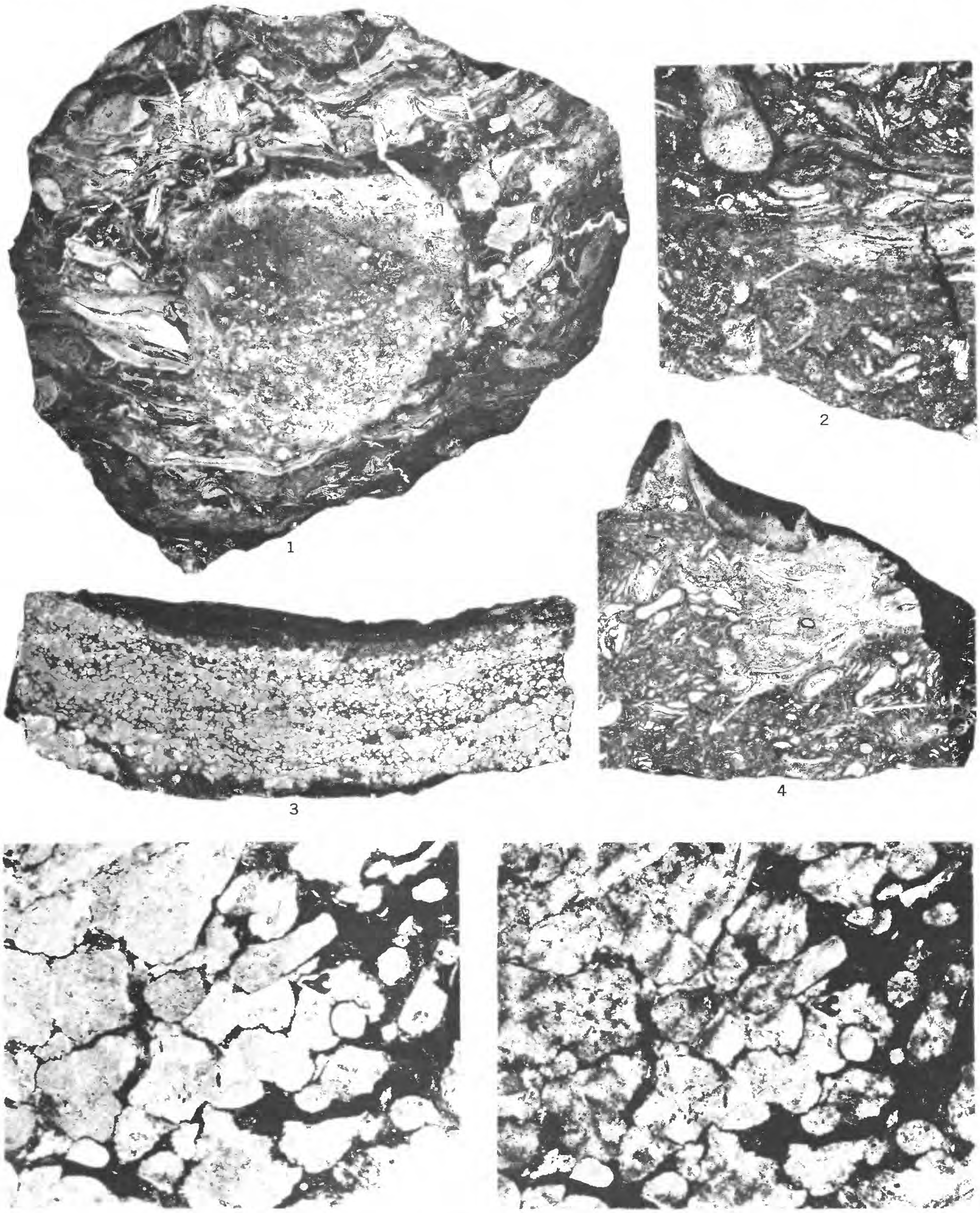
2. Broken surface of a homogeneous-mixed coal ball from Oskaloosa, Iowa, showing well-preserved plant debris. Cordaitean axis at upper left; gastropod shell indicated by arrow. Specimen 1002B. × 3. Part of this coal ball was dissolved as sample E–13.

3. Piece of limestone from Berryville, Ill., composed of coal-ball-like particles. The dark bands are streaks of coal. Specimen 9190–57. Part of this specimen was dissolved as sample E–15.

4. Part of sawn surface of homogeneous-mixed coal ball from Oskaloosa, Iowa. Several gastropods indicated by arrows. Part of this specimen illustrated in figure 2.

5. Photomicrograph of thin section cut from specimen shown in figure 3. Irregular angular and rounded particles of calcareous coal-ball-like material are tightly packed and interpenetrating. Traces of original plant tissue are still visible within the replacing calcite. Sections of two uncompressed megaspores, probably *Triletes auritus,* are shown at right. × 10.

6. Same as figure 5, taken between crossed nicols. Calcite replacement shows up as fibrous, radially arranged crystals that superficially resemble spheralites.



MIXED COAL BALLS FROM ILLINOIS AND IOWA, AND LIMESTONE FROM ILLINOIS

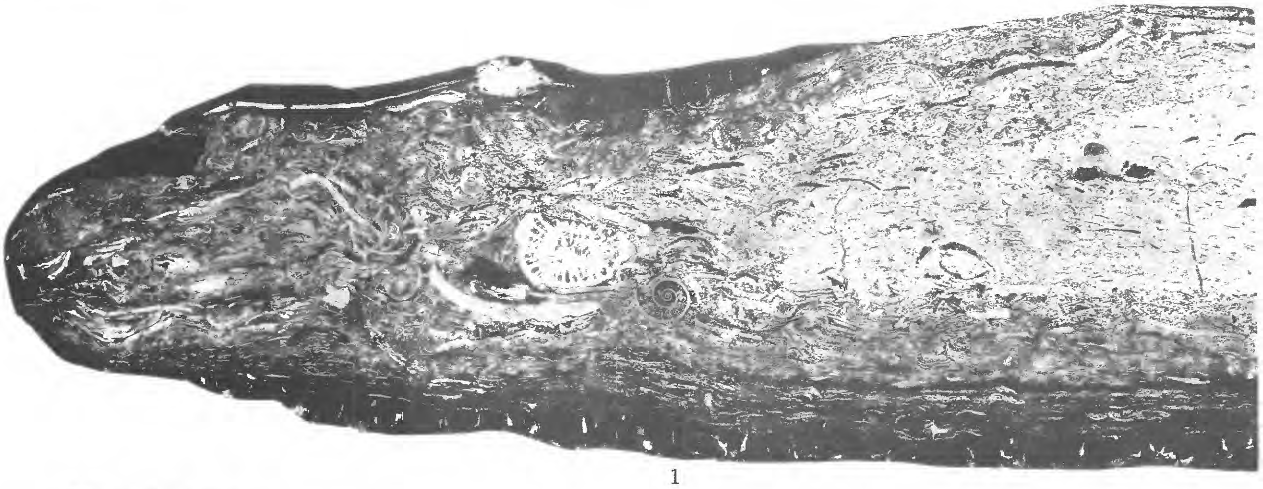
PLATE 32

[Photographs natural size]

FIGURE 1. Part of sawn surface of faunal coal ball from the Bevier coal, near Monmouth, Kans., shown in place in figures 5 and 6 of plate 26. Animal fossils exposed include sections of brachiopods and of gastropods and of a coral. Note adherent coal on upper and lower surfaces, and included coaly stringers. Specimen shown in original attitude. Specimen 9487–2E.

2. Remainder of same specimen shown in figure 1, the two pictures overlapping slightly. Black particles in left center are fusinized wood.

3. Sawn surface of faunal ball from the Bevier coal, near Monmouth, Kans., shown in place to right in pl. 26, fig. 5. The specimen is almost completely replaced by pyrite, but scattered shell fragments are visible. Specimen shown in original attitude. Specimen 9487–3A.



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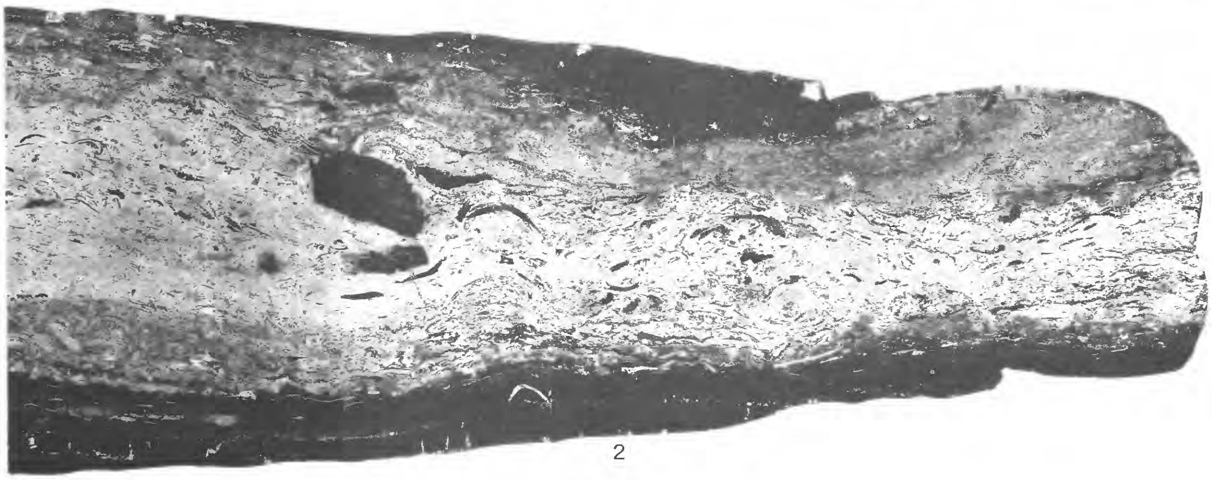

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FAUNAL COAL BALLS FROM MONMOUTH, KANSAS

PLATE 33

[All photographs made with reflected light except as indicated]

FIGURES 1–24. Spores, mostly uncompressed, and spore contents from mixed coal ball residues.

1, 2. *Monoletes ovatus* Schopf.

Proximal and distal surfaces, × 45; from residue E–3 (marine core of heterogeneous-mixed coal ball, Berryville, Ill.); USNM 41177 (fig. 1), 41178 (fig. 2).

3, 4. *Triletes glabratus* Zerndt.

Proximal and distal surfaces, × 10; from residue E–26 (marine core of heterogeneous-mixed coal ball, Berryville, Ill.); USNM 41179 (fig. 3), 41180 (fig. 4).

5–10. *Triletes* cf. *T. superbus* Bartlett.

All specimens from residue E–23 (homogeneous-mixed coal ball, West Mineral, Kans.).

5. Proximal surface of specimen denuded of equatorial frill, × 15, USNM 41181; 6, proximal surface of nearly complete specimen, × 15, USNM 41182; 7, distal surface, × 15, USNM 41183; 8, calcareous filling of spore cavity, proximal surface, × 15, USNM 41184; 9, pyritic filling of spore cavity, proximal surface, × 15, USNM 41185; 10, fragment of proximal part of endosporal membrane dissected from spore, showing numerous round dark bodies, possibly megagametophytic remains; transmitted light, × 100; USNM 41186.

11–14. *Spencerisporites* sp.

All specimens from residue E–28 (marine core of heterogeneous-mixed coal ball, Berryville, Ill.).

11. Proximal surface, × 75, USNM 41187; 12, distal surface, × 75, USNM 41188; 13, specimen photographed with transmitted light from proximal side, × 70, USNM 41189; 14, specimen photographed with transmitted light from distal side, × 70, USNM 41190.

15–17. *Triletes auritus* var. *grandis* Zerndt.

All specimens from residue E–26 (marine core of heterogeneous-mixed coal ball, Berryville, Ill.).

15. Proximal surface, × 20, USNM 41191; 16, distal surface, × 20, USNM 41192; 17, lateral view of specimen broken along two rays of trilete suture, showing hollow nature of uncompressed spore, thick exospore, and thin endospore, somewhat separated from exospore, × 20, USNM 41193.

18–19. *Triletes* cf. *T. rugosus* (Loose) Schopf.

Both specimens from residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.).

18. Lateral view of partly split but uncompressed specimen, × 30, USNM 41194; 19, lateral view of compressed specimen with segments of apical vestibule separated from each other, USNM 41195.

20. *Cystosporites varius* (Wicher) Dijkstra, × 20.

Apical view of abortive specimen showing spongy pyramidal structure at apex of spore. From residue E–31 (homogeneous-mixed coal ball, McAlester, Okla.), USNM 41196.

21–22. *Triletes triangulatus* Zerndt.

Both specimens from residue E–13 (homogeneous-mixed coal ball, Oskaloosa, Iowa).

21. Lateral-distal view, × 45, USNM 41197; 22, proximal surface, × 45, USNM 41198.

23–24. *Parasporites* cf. *P. maccabei* Schopf.

Both specimens from residue E–3 (marine core of heterogeneous-mixed coal ball, Berryville, Ill.).

23. Distal surface, × 45, USNM 41199; 24, proximal surface, × 45, USNM 41200.

25–36. Uncompressed plant parts and foraminifer-encrusted plant material from coal ball residues.

25–26. Fragments of fusinized wood, with adherent tests of *Serpulopsis* sp., × 25.

From residue E–23 (homogeneous-mixed coal ball, West Mineral, Kans.), USNM 41201 (fig. 25), 41202 (fig. 26).

27. Denuded specimen of *Triletes* cf. *T. superbus*, with adherent test of *Serpulopsis* sp., × 10.

From residue E–23 (homogeneous-mixed coal ball, West Mineral, Kans.); USNM 41203.

28. Fragment of specimen of *Triletes* cf. *T. superbus*, with test of *Serpulopsis* sp. adherent to inner surface, × 25.

From residue E–23 (homogeneous-mixed coal ball, West Mineral, Kans.); USNM 41204.

29. Oblique-lateral view of specimen of *Triletes* cf. *T. superbus*, with test of *Serpulopsis* sp. adherent to median ray of trilete appendage, × 10.

From residue E–23 (homogeneous-mixed coal ball, West Mineral, Kans.); USNM 41205.

30. Oblique-lateral view of specimen of *Triletes* cf. *T. superbus*, with two adherent tests of *Serpulopsis* sp., × 10.

From residue E–23 (homogeneous-mixed coal ball, West Mineral, Kans.); USNM 41206.

30a. Same spore, enlarged to × 25, showing conformity between *Serpulopsis* test and sinuosity of right-hand ray of trilete appendage of spore.

31. Uncompressed conostomalean seed (cf. *Coronostoma* Neeley), × 15.

From residue E–19 (normal coal ball, Berryville, Ill.); USNM 41207.

32. Uncompressed fusinized lycopod branchlet with attached leaves (cf. *Selaginellites*), × 15.

From residue E–23 (homogeneous-mixed coal ball, West Mineral, Kans.); USNM 41208.

33. Apical view of uncompressed fusinized scolecopterid fern synangium (cf. *Scolecopteris minor* Hoskins), × 30.

Tips of sporangia are broken away, showing hollow sporangial cavities. From residue E–19 (normal coal ball, Berryville, Ill.); USNM 41209.

34. Fusinized fragment of uncompressed fern pinnule, bearing scolecopterid synangium at right, × 30.

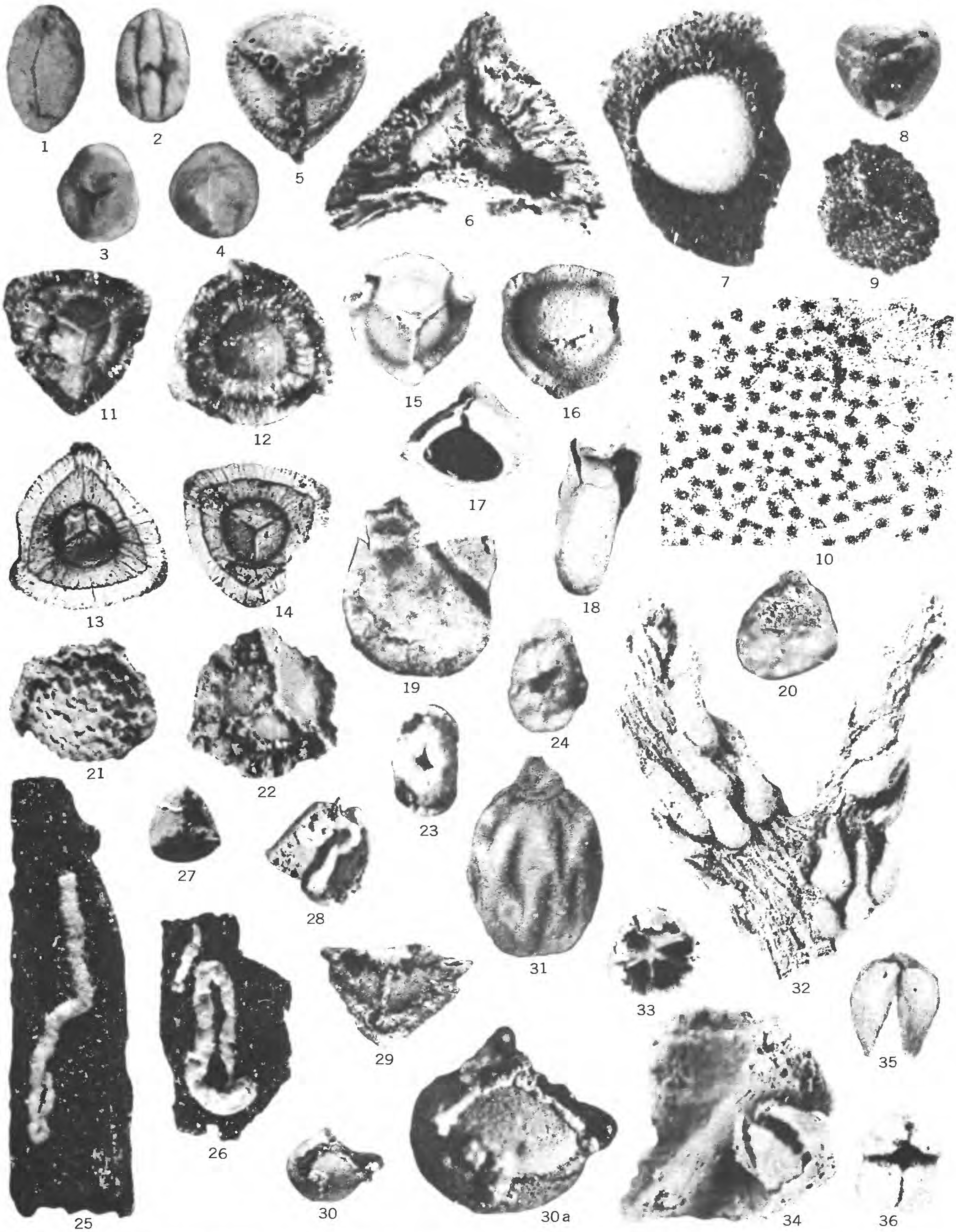
From residue E–19 (normal coal ball, Berryville, Ill.); USNM 41210.

35. Lateral view of uncompressed fusinized scolecopterid fern synangium, × 30.

From residue E–19 (normal coal ball, Berryville, Ill.); USNM 41211.

36. Apical view of uncompressed fusinized scolecopterid synangium composed of four sporangia, × 30.

From residue E–19 (normal coal ball, Berryville, Ill.); USNM 41212.



REPRESENTATIVE SPORES AND OTHER PLANT REMAINS RECOVERED FROM INSOLUBLE RESIDUES

PLATE 34

[Explanation of figures 36–57 follow plate 34]

FIGURE 1, 2. *Tetrataxis pauperata*? (Warthin), × 25.
From residue E–7, (faunal coal ball, Monmouth, Kans.); USNM 628518a,b.

3. *Globivalvulina* sp., × 25.
From residue E–31 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 628519.

4. *Apterrinella* sp., pyritic cast of undivided, tubular chamber, × 25.
From residue E–29 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 628520a.

5. *Thurammina* sp., × 25.
From residue E–27 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 628521.

6. *Ammovertella* sp., × 50.
From residue E–28 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 628522.

7. Fusulinid indet., × 25.
From residue E–31 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138848.

8. *Apterrinella* sp., with adherent sponge spicule near left end of tube, × 25.
From residue E–29 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 628520b.

9, 10. Hexactinellid sponge spicules, × 30.
From residue E–25 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138849a, 138849b.

11. *Penniretepora* sp., × 8.
From residue E–25 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138850.

12. Crinoid columnal incrusted by foraminifer, × 10.
From residue E–7 (faunal coal ball, Monmouth, Kans.); USNM 138851.

13. *Rhombopora* sp., × 10.
From residue E–25 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138852.

14. *Polypora* sp., × 4.
From residue E–25 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138853.

15, 16. *Fenestella* sp., × 10.
From residue E–25 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138854a, b.

17. Linguloid brachiopod, × 20.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138855.

18. Orbiculoid brachiopod, × 10.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138856.

19. *Derbyia* sp., × 2.
From residue E–23 (homogeneous-mixed coal ball, West Mineral, Kans.); USNM 138857.

20. *Marginifera* sp., × 2.
From residue E–23 (homogeneous-mixed coal ball, West Mineral, Kans.); USNM 138858.

21. *Mesolobus* sp., exterior, × 8.
From residue E–1 (homogeneous-mixed coal ball, Franklin, Kans.); USNM 138859.

22. *Septimyalina* sp., interior, × 10.
From residue E–31 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138860.

23. *Knightites* (*Retispira*) sp. × 5.
From residue E–20 (homogeneous-mixed coal ball, Monmouth, Kans.); USNM 138861.

24. *Eucochlis* sp., × 20.
From residue E–28 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138862.

25. *Paleostylus* (*Pseudozygopleura*) sp., × 12.
From residue E–7 (faunal coal ball, Monmouth, Kans.); USNM 138863.

26. *Shansiella* sp., × 20.
From residue E–7 (faunal coal ball, Monmouth, Kans.); USNM 138864.

27. *Parallelodon* sp., × 15.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138865.

28. *Permophorus* sp., × 10.
From residue E–31 (homogeneous-mixed coal ball, McAlester, Okla.), USNM 138866.

29. *Pseudorthoceras knoxense* (McChesney), × 4.
From residue E–31 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138867.

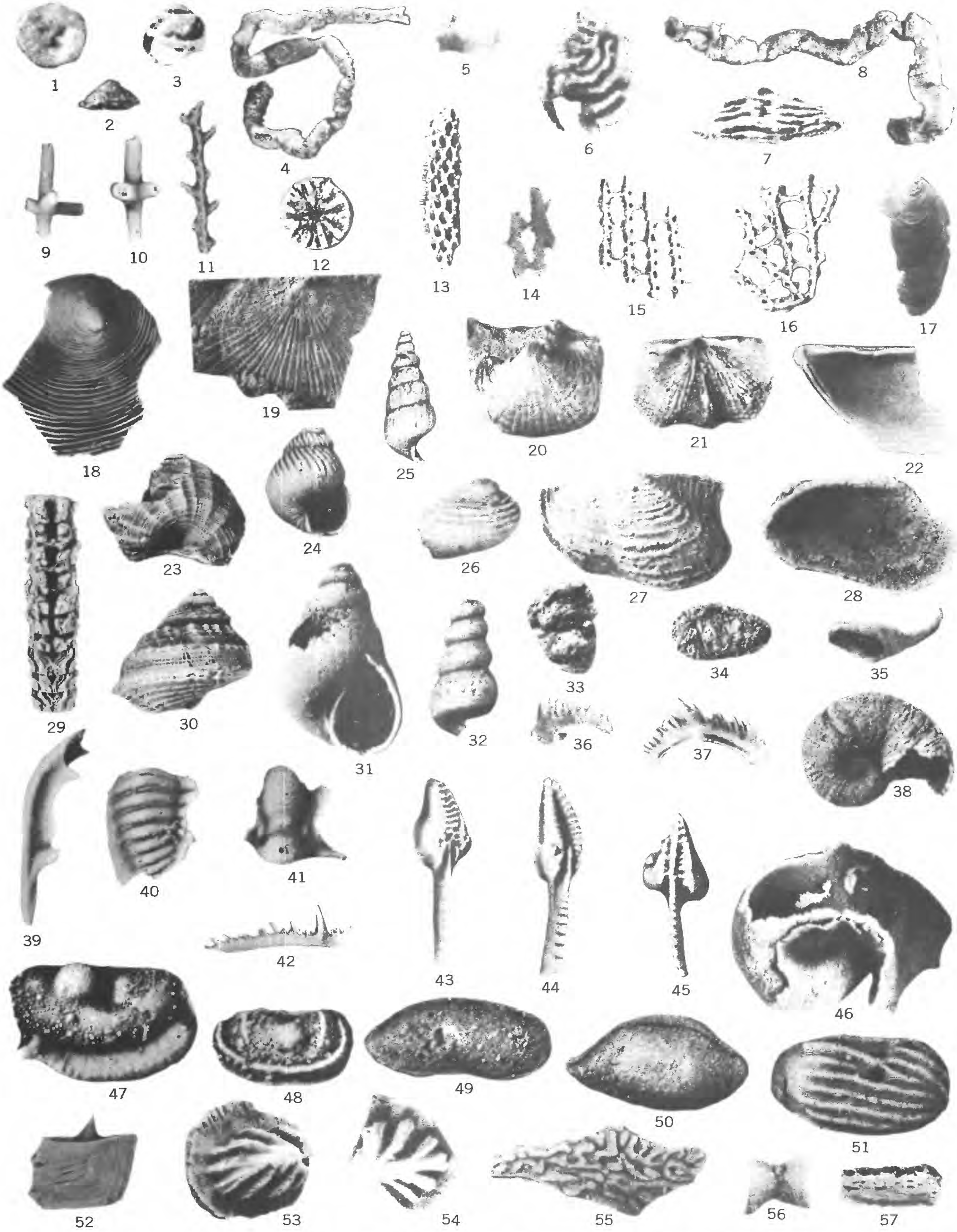
30. *Borestus* sp., × 3.
From residue E–20 (homogeneous-mixed coal ball, Monmouth, Kans.); USNM 138868.

31. Subulitid indet., slightly oblique, apertural view. × 15.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138869.

32. *Donaldina* sp., × 8.
From residue E–25 (heterogeneous-mixed coal ball, Berryville, Ill.; USNM 138870.

33, 34. Coprolitic pellets of unknown organism, × 20.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138821a, b.

35. *Arabellites* sp., × 20.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138872.



REPRESENTATIVE ANIMAL REMAINS RECOVERED FROM INSOLUBLE RESIDUES

FIGURE 36. *Spathognathodus minutus*? (Ellison), × 30.
From residue E–25 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138873.

37. *Ozarkodina delicatula* (Stauffer and Plummer), × 30.
From residue E–4 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138874.

38. "*Spirorbis*" sp., × 20.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138875.

39–41. Free cheek, fragment of pygidium, and cephalon, respectively of ?*Ditomopyge* sp., × 8.
From residue E–26 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138876a, b, c.

42. *Hindeodella* sp., × 30.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138877.

43. *Idiognathodus magnificus* Stauffer and Plummer, × 30.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138878.

44. *Streptognathodus elegantulus* Stauffer and Plummer, × 30.
From residue E–29 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138879.

45. *Gnathodus bassleri* (Harris and Hollingworth), × 30.
From residue E–13 (homogeneous-mixed coal ball, Oskaloosa, Iowa); USNM 138880.

46. "*Spirorbis*" sp. incrusted with foraminifers, × 20.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138881.

47. *Hollinella* sp., × 30.
From residue E–1 (homogeneous-mixed coal ball, Franklin, Kans.); USNM 138882.

48. *Amphissites centronotus* (Ulrich and Bassler), × 30.
From residue E–29 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138883.

49. *Bairdiacypris* sp., × 30.
From residue E–29 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138884.

50. *Bairdia* sp., × 30.
From residue E–29 (heterogeneous-mixed coal ball, Berryville, Ill.); USNM 138885.

51. *Glyptopleura* sp., × 30.
From residue E–1 (homogeneous-mixed coal ball, Franklin, Kans.); USNM 138886.

52. Actinopterygii: palaeoniscoid fish scale, × 10.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138887.

53, 54. Cladoidachii: cladodont shark scales, × 10.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138888a, b.

55–57. Actinopterygii: cranial roofing element, vertebra, and lower jaw fragment, respectively, of palaeoniscoid fish, × 10.
From residue E–22 (homogeneous-mixed coal ball, McAlester, Okla.); USNM 138889a, b, c.

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