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A KEY TO ANCIENT PLANTS

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Kinds of Fossils
To put it very simply, a coal ball is one of several different kinds of fossils. Some kinds tell us very little; some tell us a great deal. An impression, for example, is, as the name implies, simply the imprint of an object. We can measure it and perhaps observe some external features, but that's about all. A compression is much like an impression except that there is organic matter present. This is usually in the form of a cuticle (at least in plants) which, by appropriate techniques, very often can be removed from the matrix. When studied under the microscope, the cuticle frequently reveals patterns of epidermal cells, hairs, and small openings called stomata.

Molds and casts involve three-dimensional objects. If a branch, for example, would become buried in sediments, the sediments harden, and the branch decay away, a cavity (the mold) would be left behind. Then, if the mold would be filled with additional sediments which would harden, a cast would result. The cast gives us a nice three-dimensional picture of the exterior of the branch, but unfortunately nothing of the internal anatomy.

For internal structure, one must depend upon petrifactions. A petrifaction results when a mineral in solution rapidly infiltrates an organism or a part thereof, fills in all of the available spaces both within cells and between cells, and then hardens before the organic matter of the cells has a chance to decay. Contrary to a popular misconception, a petrifaction is not a molecule by molecule replacement of the organic matter by mineral. In other words, the organic matter is still there in the form of cells and tissues and can be studied by appropriate techniques.

Two of the most common impregnating minerals are silica and limestone. Most petrified wood contains silica and occasional other minerals, such as iron and aluminum. The Petrified Forest in Arizona is basically silica, but the beautiful colors of the wood are due to impurities, such as iron and aluminum compounds. Silicious woods are typically studied by thin-section techniques, since the only acid that will etch away the silica is the very potent and dangerous hydrofluoric acid.

Probably the most common type of limestone impregnated petrifaction is the coal ball, which is the main topic of this article. Although coals have been deposited during many different geological time periods, practically all coal balls were formed during one which lasted for only a relatively short
time span of about 60 million years, a period of time called the Carboniferous.

COAL BALLS

Many millions of years ago (about 300 millions to be more accurate) much of the earth's surface was covered by a swamp forest made up of plants quite different from anything living today. Some of the trees bore conspicuous markings on their bark which resembled fish scales. Another group of plants looked very much like ferns but reproduced by seeds rather than spores. These strange looking plants lived in a continuously mild, moist climate which made conditions for coal formation very favorable. Because of the large amount of coal formed from the remains of these plants, an appropriate name for this geologic time span is the Carboniferous.

Carboniferous coals are found in many parts of the world and frequently are of very high quality with practically no mineral impurities. Others are less pure, as for example Kansas and Missouri coals which contain relatively high concentrations of sulfur. Still another impurity, or obstacle to be more accurate, is the coal ball. Coal balls are limestone nodules which are usually found in the upper layers of the coal seam and which contain petrified plant fragments. The earliest coal balls which were found in Europe in the mid 1800's were invariably spherical in shape and the name "coal ball" proved to be most appropriate. We now find them in all shapes and sizes, but the name still sticks.

Nobody knows for sure just how coal balls were formed, but the presence of limestone strongly suggests an oceanic or marine environment either close by or actually covering the organic litter. We do have convincing evidence that, during the Carboniferous, a shallow ocean moved back and forth several times over the area which is now the central and east-central part of the United States. And this is precisely the area where we find coal balls. In the Appalachians, where Carboniferous coal seams are very thick, coal balls are not found. The ocean simply did not get that far east.

Coal balls were discovered and studied in Europe and much of the fundamental knowledge of coal ball plants that we have is due to the research by mid- and late-1800 paleobotanists on this European material. Here in the United States, coal balls were not recognized, at least from a scientific viewpoint, until the 1920's in Illinois. Since then, coal balls have been found and studied in many states including Kansas, Missouri, Iowa, Indiana, Ohio, and Kentucky.

Coal miners do not like coal balls because obviously do not burn and frequently are so hard and in such large masses as to make mining coal very difficult. Consequently coal balls are discarded (Figure 1) along with other mine wastes. However, to a paleobotanist (a person who studies fossil plants), such discarded coal balls are almost like Christmas presents. Open one up and you may have the find of a lifetime. They contain, as mentioned earlier, petrified plant fragments such as seeds, leaves, stems, and roots.
By studying these fragments we can gain a large amount of information concerning their anatomy and very often their morphology. We can note similarities and differences, not only among the fragments themselves but can also compare them with the few living close relatives as well. Perhaps you have seen Princess or Ground Pine (*Lycopodium*) or Horsetail or Scouring Rush (*Equisetum*) growing in the woods. These are two of the living descendents from Carboniferous plants.

Usually only the thick-walled cells and tissues are preserved, but sometimes we get remarkable preservation of delicate structures, such as root hairs, fungal hyphae, and even cell nuclei. Such finds are rare, as is the finding of a new undescribed plant part, but when they do happen, all the back-breaking labor of collecting the coal balls suddenly becomes worth while.

Studies of coal ball fossils as well as other types of fossils make it possible to reconstruct these ancient plants as we think they might have looked when they were alive. Perhaps you have seen some of these reconstructions in museums or textbooks. One of the best exhibits is at the Field Museum of Natural History (Chicago). Be sure and visit this fascinating place if you have a chance.

Now, how do we study the plant fragments contained in coal balls? We first cut the coal ball in half with a special saw (Figure 2) that has a blade with small bits of diamonds embedded in the cutting edge. The cut surface of each half is then polished by grinding.

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*Fig. 1. Pile of discarded coal balls at Illinois strip mine (Illinois State Geological Survey).*
with carborundum or some similar powder. When a smooth surface is obtained, we then "etch" the surface by immersing it briefly (10 seconds) in dilute (10%) hydrochloric acid (Figure 3). The acid dissolves away a very thin layer of limestone from the polished surface but does not affect the petrified cells, tissues, or any other organic matter exposed on the surface. Thus, after etching, the organic remains project above the coal ball surface in very slight relief.

After the surface has dried completely, we flood it with acetone and then very quickly place a sheet of cellulose acetate film on the flooded surface (Figure 4). The acetone softens and partially dissolves the film so that it slowly settles onto the etched surfaces causing the projecting organic matter to become rapidly embedded in the film. When dry and hard (usually in about two hours), the film can be pulled or "peeled" off the surface bringing with it the now embedded organic matter. We thus have a coal ball "peel" which contains a thin film or section of every bit of organic matter present on the original surface. The peel can then be examined under a microscope of low magnification to see what is present in it. If the peel looks promising, we can cut the coal ball into smaller slices and peel each new surface. In this way we "sample" the coal ball as much as is practical in hopes of finding something new or something in a better state of preserv-
Fig. 3. Etching coal ball slice in dilute hydrochloric acid (Illinois State Geological Survey).

Fig. 4. Placing sheet of cellulose acetate film on etched surface of coal ball. Surface has been flooded with acetone (Illinois State Geological Survey).
Fig. 5. Reconstruction of Carboniferous swamp forest (Field Museum of Natural History, Chicago). See Fig. 7 for key to organisms in this reconstruction.
tion than the original.

Let's say that we are lucky and find an unknown seed - what then? First we check the literature to make sure it hasn't been described before. If not, we can then proceed with the study of the seed. The peel technique makes it possible to secure progressive sections through the entire seed if we wish to do so. After the initial peel, we simply repolish and re-etch the surface and make a new peel. This process is

Fig. 6. Representative plant organs from coal balls. A. Megasporangium (M) and sporophyll from one of the scale trees, and seed fern ovule (O). B. Lycopod twig with leaves (L). C. Herbaceous lycopod stem cross section with xylem in center. D. Fern pinnule with clusters of 3 and 4 sporangia. E. Cross sections of Cordaites leaves (Illinois State Geological Survey).
repeated over and over until we have a series of peels extending through the entire seed. To observe detailed structure of the seed tissue, we cut out the portion of the peel and mount the cut piece on a microscope slide. We can then observe, under high magnification, as much detail as we can with prepared slides of living plants. By observing all of the peels in the series, we can determine the internal structure of the seed (anatomy) and its size, shape, and often its external appearance (morphology).

Unfortunately, most plant fragments (Figure 6), such as this seed, are found detached from their parent plant. One of our most difficult problems is trying to tie the various fragments together so that we have some idea of what the entire plant looked like. Like a modern Sherlock Holmes, we look for any and every clue - similarities in cell types and wall thickenings, special cells like resin or pitch cells, special kinds of epidermal hairs or glands, etc. Often the best we can do is to make an educated guess, and many of our reconstructions are based on no more than that. Wouldn't it be exciting if there were such a thing as a time machine which could take us back 300 million years and let us see just how accurate our "educated guesses" were?

Fig. 7. Key to some of the organisms shown in Fig. 5. 1 - *Lepidodendron* (scale tree), 2 - *Sigillaria* (scale tree), 3 - Cockroach, 4 - seed ferns, 5 - tree fern, 6 - *Sigillaria* (scale tree), 7 - seed fern, 8 - *Cordaites*, 9 - herbaceous lycopod, 10 - *Sphenophyllum* (sphenopsid), 11 - dragonfly, 12 - *Calamites*. 
NATURE OF THE CARBONIFEROUS SWAMP FOREST

As mentioned earlier, the plants growing in the swamp forest were quite different from plants growing today. One might even call them "weird". The climate was extremely favorable for plant growth, and the resulting forest was thick and lush (Figure 5). Although we are emphasizing plants in this article, it would be remiss not to mention that insects were also large and plentiful (Figure 7). (The Carboniferous is even sometimes called the Age of the Insects by entomologists). Cockroaches were up to 30 or more centimeters in length, and some dragonflies had wing-spans of almost a meter. Now let's take a closer look at this forest and some of its dominant plants.

Lycopods - The lycopods are represented by only five relatively obscure genera (including Lycopodium mentioned earlier), but during the Carboniferous extremely large woody lycopods, commonly called scale trees, were among the dominant members of the forest canopy. They grew to heights of about 40 meters, dichotomous branching (when present) was only near the top, and at least the upper part of the bark was covered with spirally arranged leaf cushions (Figure 8) resembling fish or reptile scales. The growth pattern, referred to as determinate, was also most unlike modern trees in that the trees could grow only so tall and no taller. The growing tip of the stem or branches became smaller and smaller, either through successive dichotomies or gradual reduction, until there was essentially nothing left for further growth. In contrast, modern trees have an indeterminate growth pattern. The underground portion of the scale trees was also most unusual in that it probably represented a modified stem system with the "rootlets" being modified leaves. Lepidodendron (Figure 9) is probably the most common of the scale trees.

Sphenopsids - Like the lycopods, the sphenopsids are poorly represented in our modern flora with only one living genus, Equisetum. During the Carboniferous, sphenopsids were quite common, with Calamites perhaps being the most representative genus. It attained a height of about 20 meters, had ribbed and jointed stems, and whorled branches and leaves. Like Lepidodendron, Calamites most likely had a determinate growth pattern.

Fig. 8. Leaf cushions of Lepidodendron.
Ferns - True ferns (as distinguished from seed ferns) were extremely abundant in the swamp forest. They were essentially very similar to modern ferns, especially the tropical tree ferns, since they grew to heights of about eight meters (Figure 10). Reproduction was by spores, typically borne in clusters on the underside of the leaflets (leaflets) just as in modern ferns.

Gymnosperms - Gymnosperms are literally naked-seed plants, as contrasted to angiosperms, which have seeds protected by a fruit. Gymnosperms were quite abundant during the Carboniferous; angiosperms (or flowering plants) did not evolve until about 170-200 million years later. There were two groups of gymnosperms prominent during the Carboniferous, the seed ferns (or pteridosperms) and the cordaites.

The seed fern, as the name implies, were plants that looked, vegetatively, very much like ferns (Figure 11), but instead of reproducing by spores, these plants bore seeds and pollen organs. The group is now completely extinct, but some botanists think they may have been involved in the origin of the angiosperms.

The cordaites (Figure 12) are also now completely extinct but were the dominant tree forms in many parts of the swamp forest. Kansas and Iowa coal
Fig. 11. Reconstruction of Carboniferous seed fern.
Fig. 12. Reconstruction of *Cordaites* branch with leaves and cones.
balls have almost 100% frequency of occurrence of cordaite fragments. On the other hand, Illinois coal balls are practically devoid of cordaite remains. No satisfactory explanation has yet been made to explain this discrepancy. Cordaites was the only Carboniferous tree having abundant wood (secondary xylem). In spite of their large size, the scale trees and calamites had little wood, using other tissues, instead, for support.

THE END OF THE CARBONIFEROUS

The Permian Period which followed the Carboniferous was marked by a pronounced change of climate, which became considerably colder and drier. (There is even evidence of Permian glaciation in several parts of the world). The result of all this was that swamps and marshes quickly dried up, and those plants that could not survive this change became extinct. In essence, the only plants that did survive to any great extent were the gymnosperms. The age of the swamp forest had come to an end, and a vast array of truly exotic and luxuriant plants was no more.

SELECTED REFERENCES