Biostratinomic Processes for the Development of Mud-Cast Logs in Carboniferous and Holocene Swamps

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PALAIOS, 1989, V. 4, p. 356–365

Prostrate trees are common features of fossil forest litters, and are frequently preserved as mud-casts. Specimens of Carboniferous mud-cast trees and a mud-filled "incipient cast" of a Holocene Taxodium *have been investigated to determine the biostratinomic processes responsible for their formation. These processes are complex. Hollowing of tree trunks may take place during life or by degradation after death. Once the trunk has fallen, the hollow cavity is supported by surrounding wood and/or bark tissues and acts as a conduit for sediment-laden waters. Leaf litter may be preserved on bedding surfaces. The infilling sequence of horizontal, parallel bedded, fine-grained sediment is deposited from suspended load during multiple overbank flooding events. These results differ from experimentally produced "pith casts" in which the sediment grain size is of fine sand. In Holocene specimens, alluvial mud within the log may provide a substrate for infaunal invertebrates. No evidence of infaunal burrowing in Carboniferous analogues exists.*

INTRODUCTION

One of the unique features of Carboniferous terrestrial vegetation is the abundance of trees and shrubs of various systematic affinities preserved as internal molds and casts. These may be of erect vegetation preserved *in situ*, or of aerial stem and branch parts lying prostrate on bedding surfaces in autochthonous/hypoautochthonous (at or near growth site) or allochthonous (transported from growth site) assemblages (sensu Gastaldo, 1988). The presence of prostrate cast trunks and branches in homogenous mudstone has been used successfully to identify the stratigraphic position of forest floor litters in ancient clastic swamps (Gastaldo, 1986a).

The abundance of internally cast plants recovered from Carboniferous strata is related to the anatomical (arrangement of tissues) and histological (types of cells comprising tissues) characteristics of the major floristic groups occupying lowland habitats during this interval in geologic history. The aerial stems of both the gymnospermous *Cordaites* (seed-bearing plants related to conifers) and the equisetalean *Calamites* (arborescent horsetails) have a hollow central pith cavity (Taylor, 1981). These pith cavities are the result of developmental factors during growth. When lateral branches are physiologically or traumatically lost, or the aerial trunk dies and falls over, the pith cavity may be exposed. This hollow void may act as a conduit when the site is inundated by sediment-laden flood waters, resulting in the deposition of terrestrial clastic mud within the axis. Deposition may be either by bedload or suspension-load sedimentation, depending upon the environment of deposition in which the plant part ultimately resides. Decay and/or coalification of the surrounding woody tissues results in the preservation of the pith casts and their distinctive morphologies.

The lycophytes (arborescent club mosses) do not possess a hollow pith, but are commonly preserved as casts due to a consistent sequence of histological decay. DiMichele (1981) notes that there is preferential degradation of the cortical tissues. This selective decay provides the mechanism for hollowing of the trunk, as well as maintenance of morphological integrity within the aerial and subterranean parts (Gastaldo, 1986b). The hollowed cavity may be infilled because the periderm (bark) tissues conserve the plant form. Often external morphological features of the plant are maintained as part of the cast. In many instances the periderm is coalified to a vitrain rind. Although lycophytes, cordaites, and calamites are the plant groups commonly preserved as casts, the other two major Carboniferous orders, pteridosperms ("seed ferns") and pteridophytes (true ferns), may be encountered infrequently in this preservational mode (Gastaldo, submitted; Table 1).

In an attempt to better understand the mechanisms responsible for the formation of internal casts of Carboniferous plants, Rex (1985) conducted flume studies to model the depositional processes for plant part casts. She used glass tubes of various small diameters in a flume laden with fine sand, and described two mechanisms for the development of these incipient casts. One mechanism was derived from bedload sedimentation; the other infilling sequence developed as the result of suspension load sedimentation. Her investigations did not include the experimental development of casts from suspension-load sedimentation of silt and clay-sized sediments. Plant casts composed of these sediments are a very common feature in the Carboniferous.

The results of our studies describe and model the tapho-

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nomic processes responsible for the development of casts of prostrate aerial tree parts in fine-grained depositional environments. We have assessed the primary sedimentary structures and bedding features in prostrate mud-cast Carboniferous lycophytes, calamites, and pteridophytes recovered from terrestrial clastic swamp environments. We have also identified and studied the "incipient casting" of a modern analogue in the clastic swamps of the Mobile Delta, Alabama. The processes we can identify in the Holocene parallel those we can infer from the Carboniferous sample.

MATERIALS AND METHODOLOGY

Prostrate casts of lycophytes and calamites have been recovered from homogenous mudstone, siltstone, and shale intervals between various coals in the southern Appalachian (i.e., Upper Cliff Coal interval, Plateau coal field, Alabama; Gastaldo, 1986a, 1987; Gastaldo et al., in press) and Black Warrior (Mary Lee and Brookwood Coal zones, Walker and Tuscaloosa Counties, Alabama) basins (Fig. 1). Logs and branches were sectioned to expose transverse and median longitudinal surfaces of the fossils. Polished cut surfaces were either sprayed with clear lacquer to accentuate bedding, or x-radiographed. X-radiographs were made of transverse and median longitudinal slabs of 1.2 cm in thickness at the Department of Radiology, School of Veterinary Medicine, Auburn University (200 MA, 1/30 sec, 72 KVP). Primary sedimentary structures were drawn with the aid of a camera lucida mounted on a Wild M8 Stereoscope. Additional specimens of prostrate logs were examined in the Field Museum of Natural History, Chicago. Specimens studied included Late Carboniferous lycophytes, calamites, and pteridophytes from Illinois and Pennsylvania.

The Holocene analog occurs in the upper delta plain (aggrading alluvial plain of Smith, 1987) of the Mobile Delta, Alabama. The specimen herein discussed is one of several hollowed *Taxodium* (Bald Cypress) trunks lying prostrate on the alluvial swamp floor in an area adjacent to the confluence of Proctor Creek and Tensaw Lake (T. 2 N. R. 2 E., Sec. 4, Tensaw, Alabama, USGS 15′ Quadrangle; Fig. 2). The log is partially buried in wet alluvial clays (McBride and Burgess, 1964) within a Deep Alluvial Swamp forest, a low diversity *Taxodium* and *Nyssa* (Tupelo Gum) community (Stout et al., 1982). Prior to logging in the 19th and 20th centuries, these alluvial swamp communities were monotypic, dominated by *Taxodium*. The orientation of the log was noted in relation to Proctor Creek, its parent stump located, spatial relationship noted, and dimensions (length, diameter, hollowed area diameter) recorded (Fig. 3). Wood subsamples were taken to: 1) examine histological features and extent of decay utilizing SEM; 2) determine the approximate tree age using dendrochronology; and 3) radiocarbon date the wood to ascertain when the plant was living (Center for Isotope Studies, University of Georgia).

The part of the prostrate log above the forest floor was cut open with a chain saw to obtain access to the infilling flood-derived mud. The surface of the sediment was described, the thickness of the clay deposit was recorded at 10 localities, the sites of bioturbation by crayfish (*Cambarus diogenes*) were noted, and a subsample for XRD was obtained (Fig. 3). Can cores oriented parallel and perpendicular to the axis of the log were recovered. Due to the highly saturated character of the alluvial mud, standard recovery techniques had to be modified. Plexiglas can cores (14 × 12 × 2 cm) were constructed in a C-shape, without tops. Two frames were inserted into the mud with the back of each can core touching. A hand-held stainless steel box coring device (Scheihing and Pfefferkorn, 1984) was then inserted over the area. The box core device with enclosed plexiglas can cores was then removed. The sediment sample was recovered from the box core and separated along the plane established between the backs of the can core frames. Sheets of used newspaper tintype were used to cut along the unsupported edge of the can core, plexiglas covers were placed on the cut surface, and cores were secured in plastic food wrap. Can cores were X-radiographed. Five cores (1,2,3,4,10) were disaggregated to confirm the x-radiograph findings. Two cores

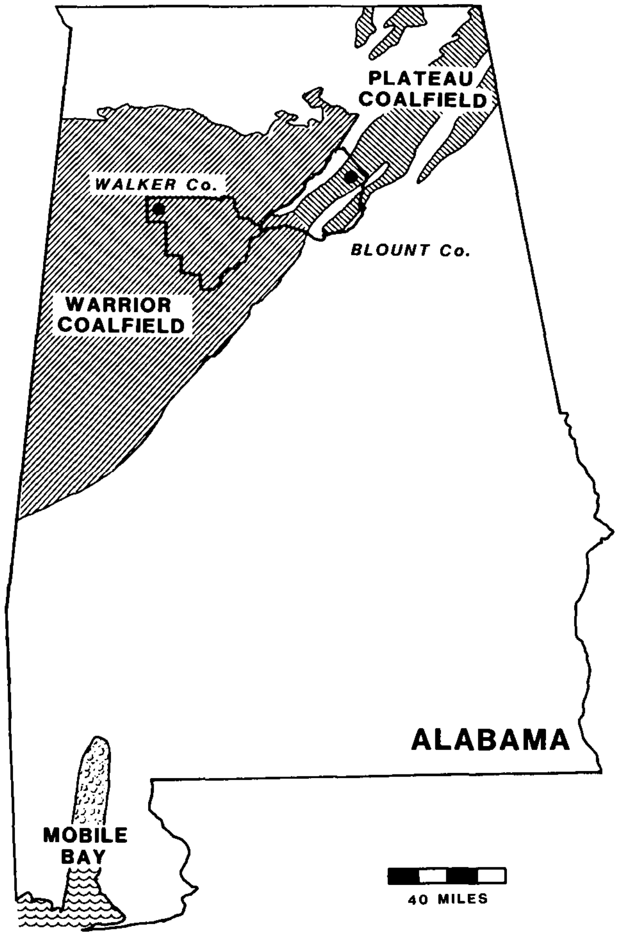

FIGURE 1—Locality map of study sites in Alabama. Carboniferous samples were collected from Blount County, Plateau Coalfield, and Walker County, Warrior Coalfield. Holocene samples were collected in the upper delta plain of the Mobile-Tensaw River Delta, Baldwin County.

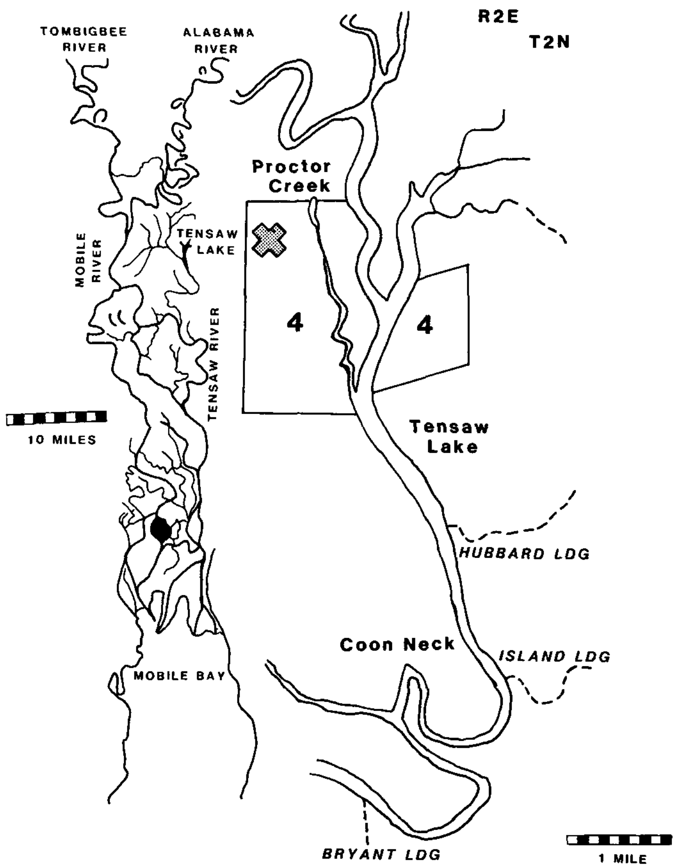

FIGURE 2—Map of the Mobile-Tensaw River Delta. Insert map shows the location of the sampled prostrate *Taxodium distichum* log in the Deep Alluvial Swamp community (Stout et al., 1982) adjacent to Proctor Creek. See: Gastaldo (1989) for details of the upper delta plain.

(5,11) were allowed to dry in an attempt to accentuate layering or compositional differences. Recovered macrodetritus was identified.

RESULTS

Carboniferous Specimens

Casts of prostrate aerial parts commonly are of various dimensions, depending upon the length and diameter of the original part resident in the depositional environment. These parts are generally oriented parallel to bedding features. The casts are elliptical in transverse section, reflecting an incomplete infilling and original configuration of the void. Lower surfaces of the casts are usually more convex due to support by the matrix. Prostrate casts are easily distinguished from erect *in situ* trunks both by their orientation within a lithotope and their cast shape. Erect trees cross-cut bedding and other sedimentary structures. They are round to oval in transverse shape, reflecting the approximate original shape of the tree (Gastaldo, 1986b).

Lycophytes are the most commonly encountered plants preserved as mudstone-casts because of their ecological role as the dominant deep swamp community element (Gastaldo, 1987; DiMichele and DeMaris, 1987). These plants are identified by characteristics of the bark (including helical arrangement of leaf cushions, discontinuous or continuous linear markings of bark tissues, or traces of vascular or parichnos tissues). One lycophyte will serve as an example for descriptive purposes; characteristics of additional curated lycophytes and other mudstone-cast specimens are provided in Table 1.

The specimen (Fig. 4) is part of an internal cast of the aerial trunk section from a lycophyte. This lycophyte is unassigned to any specific taxon due to the absence of leaf cushions, these having been sloughed during growth. This is common in some species of *Lepidodendron* (Wnuk, 1985) and in *Lepidophloios* (pers. obs., Gastaldo, 1987). The trunk section was enclosed in a mudstone and protruded from an active mine high wall above the Rosa Seam, Blount County, Alabama (Berry Mountain Mining Company, T. 11 S., R. 2 E., Sec. 31, Clarence, Alabama, 7.5′ Quad). The recovered fragment measures 31 cm in length, 20 cm in width, and is 3 cm in maximum thickness in the center of the stem. A thin (less than 1 mm) coaly rind was present on the fragment. The trunk is elliptical in transverse section, with the ridges of bark tissue well distinguished (Fig. 5).

X-radiographs of a transverse and median longitudinal slab illustrate that there is an area of less density in the center of the cast (Fig. 5). Distinguishable sedimentological features reflect bedding that is principally parallel and flat-lying both in transverse and longitudinal section. Because of the possibility that there may be a ripple structure present in longitudinal section, at the interface of the more and less dense zones, camera lucida drawings were made of the longitudinal surface to verify the existence of this feature (Fig. 6). It is evident from the drawing that the laminae are parallel without any indication of developed ripple structures. The parallel laminae are preserved on a slight angle near the base of the specimen, and there does not appear to be any indication of graded bedding between laminae. Although not preserved in this specimen, coalified compressions of aerial plant parts may be preserved on bedding surfaces within the infilling sequence (Table 1).

Taxodium Analogue

The prostrate *Taxodium* trunk lies partially buried in the swamp floor. It is oriented in an west-northwest direction and displaced about 2.8 m from its parental stump (Fig. 3). The erect parent stump is 3.0 m in height, hollowed, and partially infilled with alluvial mud. The prostrate log measures 15.45 m in length, but only the central 5.1 m remains cylindrical. The distal and proximal parts of the log are partially degraded. The diameter of the trunk averages 0.45 m, with the hollowed interior portion averaging 0.25 m in diameter. The thickness of the wood forming the cylinder averaged 5 cm, and the interior surface is characterized by discontinuous parallel ridges, bumps, and valleys having a relief of less than 5 cm.

The C-14 dated wood sample is taken from the inner edge of

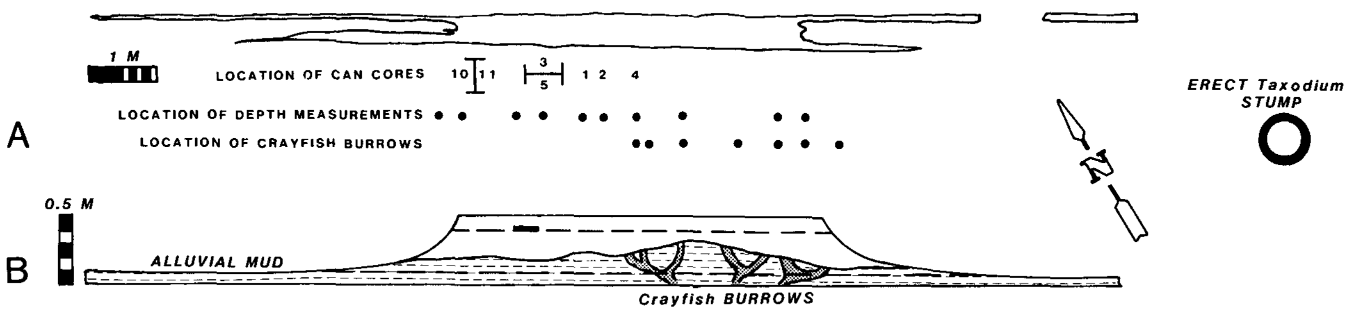

FIGURE 3—Line illustration of sampled prostrate *Taxodium*. **A)** Aerial view of prostrate log in relation to hollowed erect parental stump. Location of can cores recovered from the mud infill include two transverse cores (10,11), and five median longitudinal cores (1,2,3,4,5). Locations of depth measurements of infilled mud and location of crayfish burrows are used as the basis for the reconstruction in B. Scale equals 1 meter. **B)** Reconstruction of log in side view with one half of the log removed. Dashed line in cylindrical portion of trunk represents the remaining thickness of wood. Alluvial mud is thickest near the center of the log and may be the result of bioturbation. Darkened area represents site of wood sample taken for C14 and SEM analyses. Scale equals 0.5 meter.

the wood cylinder, a depth of 5 cm from the bark. The C-14 date on this part of the tree is 539±50 YBP (UGa-5824, Del ^{13}C : -26.27; normalized to 1950 A.D.). Because the C-14 dated wood represents only the interior annual rings of the hollowed log, dendrochronologic analysis was required to determine the age of the tree. It is found that 33 growth rings exist in 1.5 cm of transverse distance across the wood. Extrapolating back to the initiation of tree growth indicates that the tree began growing about 936±50 YBP. It died approximately 430±50 YBP. It is impossible to estimate when the trunk began to rot and fell from the stump to the alluvial swamp floor. There are a few living *Taxodium* in the swamps in which the central portions of the trees are hollowed. Hollowing of this specimen may have begun during life. Not all *Taxodium* begin internal hollowing during life, though.

Scanning electron micrographs of the *Taxodium* wood reveal that very little biodegradation has occurred (Fig. 7). The rate of decay is apparently very slow. This is not surprising because cypress is well known as a resistant wood, and it has been logged particularly for that purpose. What is surprising, though, is that very few fungal hyphae were encountered within the tracheary elements (conducting cells; Fig. 7). Most of the biodegradation appears to be related to boring insects (a few of which were encountered during removal of the upper portion of the wood cylinder) and the subsequent introduction of fungi into these tunnels. Insect boring helps to account for the irregularities in surface texture of the inner cylinder. The ends of the trunk are the most susceptible to insect boring and degradation proceeds from the ends of the trunk to the middle (see Fig. 3).

The infilling sediment is a very fine-grained clayey mud with no discernible coarser (silt) clastic component. McBride and Burgess (1954) characterize this soil as a Wet Alluvial Clay. Mud composition was analyzed using X-ray diffractometry. The mud consists of 30–40% montmorillonite, 20–30% disseminated quartz, with the remainder organic material. This mud is slightly higher in relief than the mud surrounding the prostrate log. On the day the samples were collected, there was approximately 4 cm of standing water in the swamp. The level of the standing water did not cover the mud in the central portion of the hollowed log. The surface of the infilling sediment is characterized by a mat of leaves and twigs (mat of 1–2 leaves in thickness) in both the exposed (top of the cylinder rotted away) and enclosed (within the wood cylinder) portions of the trunk. The thickness of infilled mud averages 0.13 m, but due to the irregularities in the bottom of the hollowed trunk, mud thickness ranged from 0.09 m to 0.19 m. The thickest accumulations are near the middle of the enclosed trunk section; the thinnest accumulations are near the ends of the log. Crayfish burrows, some with chimneys, were common in the protected cylindrical area (Fig. 3B). Several low relief mounds, probably old collapsed burrow chimneys, are also present.

X-radiographs of box cores illustrate the alternate layering of alluvial mud and plant macrodetritus (Figs. 8, 9). Three distinctive parallel layers can be discerned in Cores 1 (Fig. 8B, 9B) and 5, in addition to several indistinct layers. Two parallel layers can be identified in Cores 2, 3 (Figs. 8A, 9A), and 4 with the uppermost layer either missing, destroyed by bioturbation (see below), or not well defined. The basal layer averages 5 cm in thickness (4–7 cm) and contains only woody fragments. The top of the basal layer is easily delimited due to an oxidized layer of iron resulting in a density difference on the X-radiographs. An accumulation of Spanish Moss (*Tillandsia usneoides*) of less than 5 mm in thickness also occurs along the top of this basal layer. The upper portions of the cores show distinctive laminate structures. Leaves, wood, bark, and seeds are common throughout the sediments (Figs. 8, 9).

Plant parts are concentrated on the bedding surfaces of the principal layers identified. The most common plant macrodetritus recovered from the disaggregation of cores includes leaf material (*Nyssa*, *Taxodium*, and unidentifiable deciduous angiosperms), thin twigs (*Nyssa*, *Taxodium*, and unidentifiable), Spanish Moss (*Tillandsia usneoides*) consisting of branching stems with filiform leaves, seeds (*Nyssa*), and unidentified bark and unrounded wood fragments. Macrodetritus is more concentrated towards the ends, with the amount decreasing towards the middle of the log. The centrally located Core 4 is without appreciable plant detritus.

TABLE I—Carboniferous lycophyte, calamite, and pteridophyte logs that are preserved as mud-casts and curated in the Paleobotany Collections of the Chicago Field Museum of Natural History, Chicago, Illinois. All dimensions are in cm. TS indicates that parallel laminations are evident in transverse section; LS indicates that parallel laminations are evident in longitudinal section.

	GENERIC ASSIGNMENT	LOCALITY	LENGTH	WIDTH	THICKNESS	EVIDENT PARALLEL LAMINAE	EVIDENCE OF RIPPLES (R) OR LATERAL ACCRETION (LA)	NUMBER OF LEAF LITTERS INCORPORATED	COALIFIED PERIDERM
LYCOPHYTES									
P 1226	Lepidodendron	Cabinet 1415	43	38	1	TS, LS	NO	NO	ABSENT
P 1256	Sigillaria	Pennsylvania	58	29	2	TS, LS	NO	NONE	ABSENT
P 5691	Sigillaria	Washington Co, PA	30	45	1.9	TS, LS	NO	YES—3	ABSENT
P 8609	?Diaphorodendron	Ziegler, IL	26	7.5	1.5	TS, LS	NO	NO	PRESENT
P 22070	Sigillaria	Plymouth, PA	34.4	40	1.6	TS	NO	YES—3	PRESENT
P 22069	Sigillaria	Cannelton, PA	29	23.8	1.8	TS	NO	NO	ABSENT
UP 1101	Indeterminable	Christopher, IL	21 cm	15.5 cm	1.1 cm	TS	NO	NO	ABSENT
UP 1181	Sigillaria	Cabinet 1411	31	11.3	1.1	TS, LS	RESTRICTED TOP—R	NO	PRESENT
UP 1196	?Diaphorodendron	Pittston, PA	26.8	14	0.9	TS, LS	NO	NO	ABSENT
UP 1234	Sigillaria	Olyphant, PA	18	10.3	0.4	TS	NO	NO	PRESENT
UP 1301	Lepidodendron	Pittston, PA	30	19	1.2	TS, LS	NO	YES—1	ABSENT
UP 1620	Indeterminable	Danville, IL	28	12.3	1.8	TS, LS	YES—LA	NO	ABSENT
UP 1675	Indeterminable	Illinois	34	25.5	3.8	TS	NO	NO	PRESENT
UP 1695	Sigillaria	Illinois	24	17.5	1.8	TS, LS	YES—LA	NO	ABSENT
UP 1696	Indeterminable	Illinois	32	20	0.9	YES	NO	NO	ABSENT
UP 1967	Indeterminable	Harrisburg, IL	27.5	15.5	2.2	TS	NO	YES—1	PRESENT
UP 2249	Sigillaria	Pittston, PA	40	20.5	0.8	TS, LS	NO	NO	ABSENT
UP 2313	Sigillaria	Cabinet 1413	45	20	3.3	TS, LS	NO	NO	ABSENT
UP 2314	?Sigillaria	Harrisburg, IL	30	26.6	0.8	TS	NEAR TOP—LA	NO	PRESENT
UP 2600	Indeterminable	Illinois	26	13.5	0.8	TS	NO	NO	ABSENT
UP 2798	Indeterminable	Cabinet 1313	103	13	1.4	TS	POSSIBLE—R	NO	ABSENT
UP 2957	?Diaphorodendron	Cabinet 1415	62.5	25	1	TS	NO	YES—1	PRESENT
CALAMITEANS									
P 8607	Calamites	Zeigler, IL	44	16	4	TS	YES—LA	NO	ABSENT
UP 2796	Calamites	Cabinet 1414	30	15.5	2.2	TS	NO	NO	ABSENT
PTERIDOPHYTES									
UP 428	Caulopteris	Cabinet 1414	29.5	16	1.4	TS	NO	NO	ABSENT
UP 429	Megaphyton	Harrisburg, IL	17	15.5	1.8	TS, LS	NO	NO	ABSENT
PP 11793	Caulopteris	Cabinet 1415	53.5	12.5	2.8	TS	NO	NO	ABSENT

Bioturbation observable in x-radiographs is restricted to horizontal terete burrows, approximately 3 mm in diameter. These burrows are surrounded by oxidized sediment and are present in the uppermost layers of Core 3 (Figures 8A, 9A). Crayfish burrows are present within the log (Figure 3) but were avoided during coring due to the inherent problems of maintaining sediment and burrow integrity. These burrows are clustered in groups of three, and consist of one chimneyed burrow and two interconnected, non-chimneyed burrows. These burrows did not penetrate through the bottom of the prostrate tree. The crayfish that probably built the chimneyed burrows is *Cambarus diogenes*, a taxon widely distributed in eastern North America (Crocker and Barr, 1968). One individual is responsible for a single interconnected burrow cluster. Groups of burrow clusters that are not interconnected usually represent activity by several adults (Grow and Merchant, 1979). Crayfish parts are uncommon in the mud, although a partial appendage was recovered from Core 10.

DISCUSSION

Infilling Processes

The biostratinomic processes responsible for the development of mud-cast logs in the Holocene and Carboniferous are similar. In both instances the "incipient cast" and the lithified casts are typified by multiple, horizontal layers. The horizontal, parallel bedding of the infilling mud is considered to be the result of suspension-load deposition over a period of several overbank flood events. This interpretation is supported by the

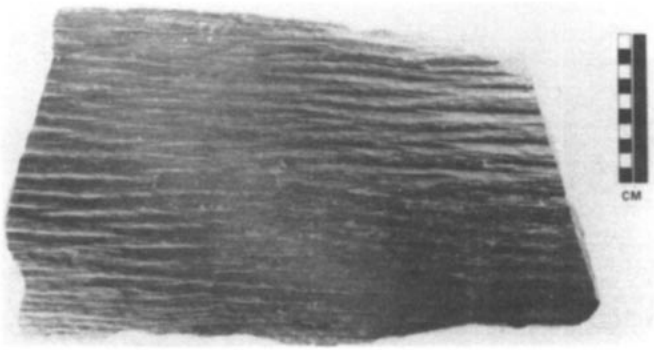

FIGURE 4—Photograph of mud-cast, unidentifiable lycophyte trunk recovered from a Carboniferous clastic swamp, Blount County (Gastaldo, 1987). Leaf cushions are not preserved due to their loss during expansion in tree diameter. Specimen was cut transversely (see Fig. 5) and median longitudinally (see Fig. 6) for examination. Scale in cm.

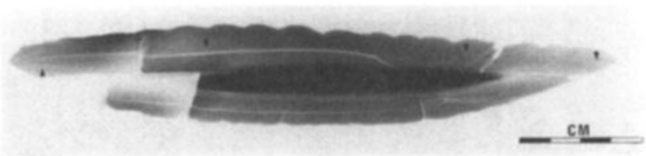

FIGURE 5—X-radiograph of transverse section of lycophyte specimen in Figure 4. Note that the lower surface of the prostrate log is slightly arcuate and does not preserve the ridge structure as well as the more flattened upper surface. Parallel laminae are visible in the denser portions of the specimen (at arrows), whereas slightly inclined laminae occur in the central part. Scale in cm.

laminate character of the infilling mud, the presence of oxidized zones between beds, and concentrated plant macrodetritus on more than one bedding surface of the *Taxodium*-fill and some of the Carboniferous specimens (see Table 1). Suspension-load mud is introduced into these levee-bound swamps during flood events in which the water level tops the levee and fills the interdistributary area.

The process of infilling may be complex. Sediment-laden water flowing through the hollowed log may respond similarly to a pipe with rough boundaries. The irregular interior surface of the log will provide resistance to water flow thereby reducing velocity within the cavity. A reduction in flow velocity will affect the vertical velocity, resulting in an increased settling velocity (Blatt et al., 1980). Deposition will ensue. If sediment-laden waters flow through a hollowed prostrate log, one would expect to find a thicker accumulation of mud within the cavity than surrounding the log. This condition was noted for the *Taxodium* log. Each identifiable bedding (layering) features is the result of a single flood event. Multiple flood events infill the cavity over time (see below).

On the other hand, as flood level subsides, mud is deposited from suspension-load from the flood waters that remain resident within the swamp and within the plant cavity. Although standing water may be found within portions of the swamp during the year or may be introduced by rainfall, mud deposited by flood events is rarely resuspended (pers. obs.). Resuspension occurs when one plunges his/her foot into the swamp mud, and these clasts remain locally suspended for several weeks before settling (pers. obs.). When meteoric waters are introduced onto the swamp floor, the thin mat of canopy litter acts as a barrier to resuspension.

Wood of *Taxodium* is very resistant to decay and once the central part of the trunk is hollowed, the cavity can be maintained for a long period of time. The maintenance of the cylinder provides the site for accumulation of mud and the "incipient casting" of this plant. A similar situation probably existed for the Carboniferous *Calamites* and *Cordaites* whose hollow pith was supported by a surrounding cylinder of pycnoxylic wood. In the case of the Carboniferous lycophytes, though, the resistant character of the periderm (bark) maintained the trunk/branch integrity. Cavities were filled to various degrees as the axis lay prostrate on the forest floor. Subsequent burial and compression imparted the characteristic morphological features of the plant to the exterior of the fill.

The relative time of residence on a forest floor can be calculated for the Carboniferous specimens if certain assumptions are made. First, one must assume that each layer of mud now compacted and lithified represents deposition from a single flood event that overtopped the levee and filled the interdistributary swamp. Second, that overbank flood events in modern tropical deltas occur on the average of 20 years. Natural levees are not overtopped by annual flood events, but rather by more severe flooding. Pfefferkorn et al. (1988) have found that severe floods in the Orinoco Delta, Venezuela, occur on the average of 19.2 years. Severe floods are defined as those in which the peak flood stage is up to 5 m above normal annual flood stage, and this rise in water level may occur within less than half a day. Third, that the incomplete filling of prostrate logs is due to an anomalous, high-sedimentation flood event that results in the burial of the forest litter. Again, Pfefferkorn et al. (1988) recognize 100-year flood events in which sand bars are deposited by fluvial mechanisms on top of levees consisting of silt and clay. Such an intensive flood, or more catastrophic floods (1,000-year flood), would provide significant quantities of sediment that would bury the forest floor litter. In a tropical climate analogous to the modern one, the lycophyte specimen in Figure 4 would have been resident on the swamp forest floor for approximately 400 years.

Bioturbation

In the case of the Holocene example, bioturbation principally by crayfish has played a significant role in alteration of the "incipient cast." Crayfish burrows occur along the levee and the levee/deep swamp ecotone, as well as in open areas of the deep swamp and in hollow, sediment-filled, prostrate logs. All crayfish prefer to hide under debris in standing water during daylight hours (Crocker and Barr, 1968). The hollowed logs provide not only a preferable hiding place, away from the various predators in the swamp, but also a substrate in which to burrow. The collapse of their chimneys may provide for small-scale localized deposition within the log. The absence of

FIGURE 6—Camera lucida drawing of median longitudinal section of specimen in Figure 4. Note that only horizontal laminae continue across the 10 cm of distance illustrated. Scale in mm.

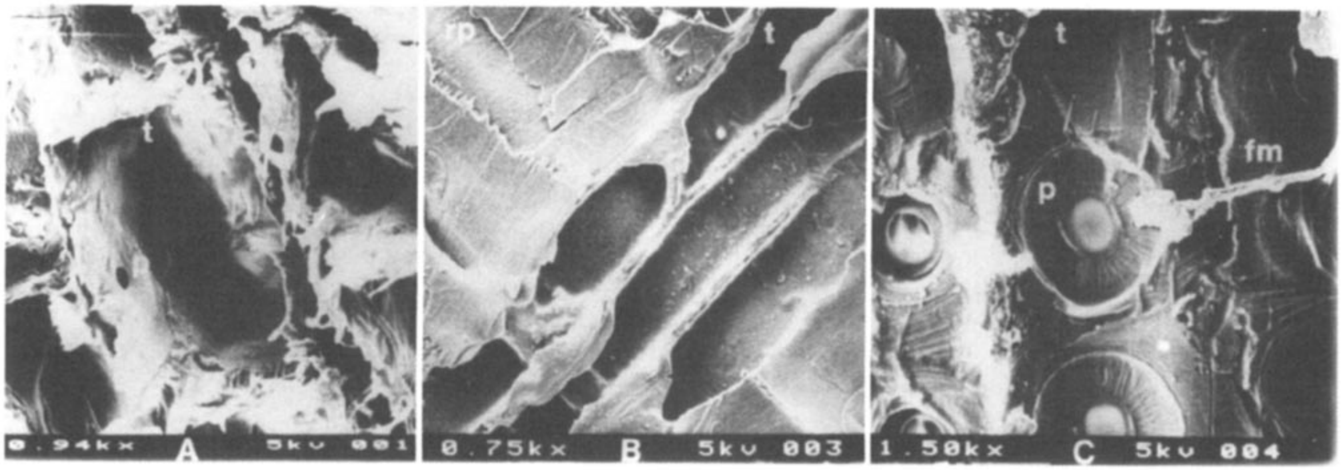

FIGURE 7—Scanning electron micrographs of Holocene *Taxodium distichum* wood recovered from the interior of the hollowed log. **A)** Transverse view showing tracheids (t, conducting cells) and bordered pits (p). Note the absence of fungal hyphae. **B)** Radial view of wood sample illustrating parenchyma ray cells (rp) and hollow tracheids (t). Note the absence of fungal hyphae in either the tracheids or associated with the parenchyma cells. **C)** Tangential view of wood sample illustrating tracheids (t) and circular bordered pits (p). One fungal mycelium (fm) is present attached to the circular bordered pit.

sedimentological structures in the basal deposit and the character of the uppermost layers in several Can Cores (1,2,4, and 5) may be a reflection of this process.

Crayfish consume terrestrial plant matter and burrowing forms feed largely on subsurface plant debris (Crocker and Barr, 1968). Canopy detritus occurs within the log and is abundant throughout the swamp. Crayfish burrowing activity disrupts the primary sedimentary structures and churns plant detritus into the mud. Such activity may account for the presence or absence of plant parts encountered within any particular layer (e.g., Can Core 1, Fig. 9B).

It is worth noting the complete absence of bioturbation in the Carboniferous casts herein documented, in any prostrate or erect-cast tree encountered by the senior author within the past 15 years, or in any publication in which erect trunks are documented (see: Gastaldo, 1986a). In addition, it is worth noting that burrowing structures in clastic swamp paleosols have not been reported in the literature. Gastaldo et al. (in press) have noted what appear to be burrowing structures in such paleosols in the Plateau Coalfield, but further investigations are needed to confirm this interpretation. The absence of bioturbators in these coastal lowland swamps suggests that Carboniferous invertebrates had not yet evolved to the point of being capable of infaunal adaption under these terrestrial conditions.

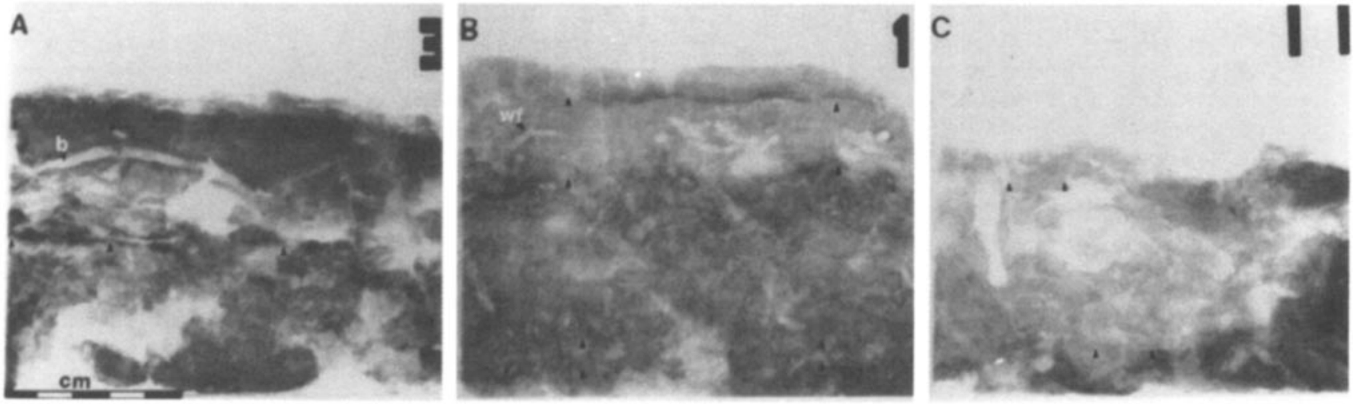

FIGURE 8—X-radiographs of Can Cores 3, 1, and 11 (See Figure 3 for location of can core sample sites). Scale same for all x-radiographs; scale in cm. **A)** Can Core 3 represents a longitudinal view (parallel to axis length) through the "incipient cast." A leaf litter layer occurs on the top and plant detritus is incorporated throughout. At least two bedding surfaces can be discerned (at arrows). Small burrows (b) occur in the upper left of the can core. See Figure 9A for a graphic interpretation. **B)** Can Core 1 represents a median longitudinal view through the "incipient cast." At least four bedding surfaces (excluding the subaerially exposed surface) can be discerned (at arrows). No burrows were encountered in this core, but a wood fragment (wf) is evident. See Figure 9B for a graphic interpretation. **C)** Can Core 11 represents a transverse median view (perpendicular to axis) through the "incipient cast." Bedding surfaces are difficult to discern (at arrows). Plant macrodetritus is incorporated throughout the section. See Figure 9C for a graphic interpretation.

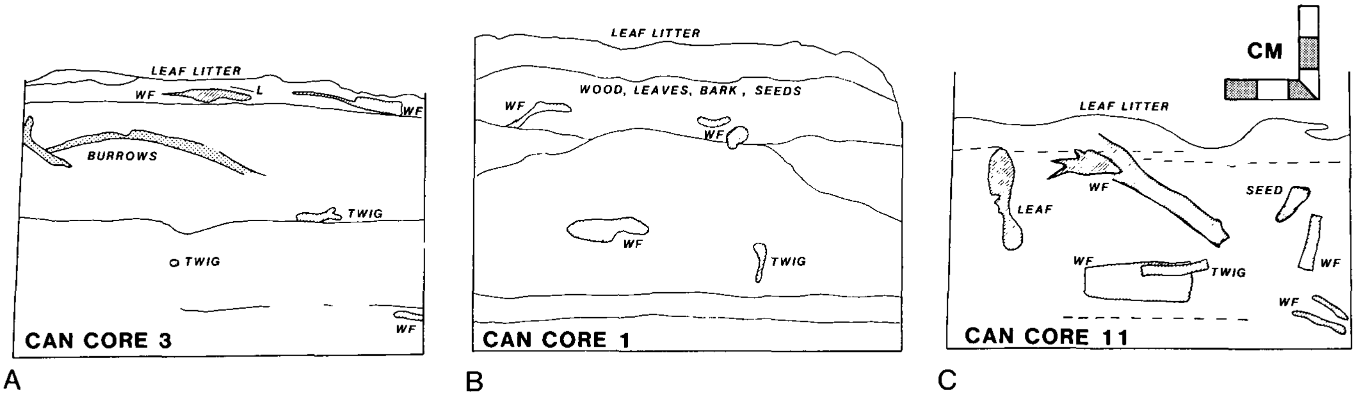

FIGURE 9—Line illustrations of tracing made from Can Cores. WF indicates the presence of wood fragments, L indicates leaf material, and other plant parts are labeled. Scale in cm. **A)** Illustration of X-radiograph 8A. **B)** Illustration of X-radiograph 8B. **C)** Illustration of X-radiograph 8C.

Incorporation of Plant Macrodetritus

Plant macrodetritus can be introduced onto the exposed bedding surface in either of several ways. Floating litter may be introduced into the cavity as a flood event ebbs. Leaves and branches may fall from the canopy of the surrounding vegetation and become incorporated in those areas where the trunk is no longer cylindrical in shape. In the Holocene example, the concentration of Spanish Moss along the top of the lowest bedding surface may have been brought into the log as bedding material by an indigenous mammal.

The presence of multiple plant-bearing beds within Carboniferous and Holocene hollowed and infilled logs indicates that hiatuses occur between major flooding events. The infilling sequence does not represent a single depositional event. The absence of plant litter on bedding surfaces, though, is probably an indication that the bedding surface was subaerially exposed. Plant materials on these bedding surfaces decayed and were incorporated into the mud, contributing to their organic-rich coloration. This is particularly true in the Carboniferous specimens. Not all plant material introduced into the cavity will be preserved. Only those litter layers that are covered shortly after deposition, possibly only after a few years, have the potential of fossilization. The presence of compression fossils on a bedding surface, therefore, suggests two closely spaced severe flood events.

Comparison with Previous Experimental Studies

Rex (1985) reports on a series of experiments conducted in a restrictive flume to investigate the formation of plant "pith casts" using fine sands in suspension and bedload. A single continuous run of the flume was used to create each incipient cast. A 1.5 cm diameter glass tube was used to simulate a pith cavity. It is not reported whether natural fluctuating flow conditions were simulated. Experimentally derived suspension-load infills are characterized by a basal horizontal layer of sediment. This is overlain by distinct wedge-like sediment accumulations (cross-laminated avalanching wedges) at either end of the glass tube. These wedges accumulate in response to vortices developed by pressure differences at each end of the small diameter tube (Bernoulli effect). The wedges migrate towards the middle. When obstruction of the stem cavity occurs by the wedge topset, cessation of infilling results in a centralized void. The incomplete infilling of the central portion of the stem appears to be directly related to stem length.

Comparison of our results with those of Rex (1985) support the contention that suspension-load infilling via sedimentation of fine terrestrial clastics differs sharply from depositional mechanisms proposed for infilling by fine sands. Analyses of x-radiographs of the *Taxodium* "incipient cast" and Carboniferous counterparts reveal that parallel, horizontal lamination is the principal sedimentary structure throughout the length of the casts. The horizontal, planar character of these beds is maintained throughout the "incipient cast" of the *Taxodium* and in those Carboniferous forms examined in longitudinal profile (e.g., Fig. 6). In a few Carboniferous representatives (Table 1) lateral accretionary beds can be discerned in transverse section, but it appears that these beds remain horizontal and parallel throughout their longitudinal distance. In none of the specimens examined was there evidence of cross-bedding following the axis of the cavity. In addition, the specimens herein documented are infilled completely from one end to the other. There is no void towards the middle of the stem. Rather, mud deposition appears to be thickest where the cylinder has maintained its integrity.

The described differences may be the result of one or more factors. The most obvious difference is grain size. The finest clastics used in the experiments conducted by Rex (1985) did not exceed 0.1 mm (3ϕ), whereas deltaic mud is clay-sized (8ϕ). Her model suggests that the wedges at either end of the small diameter "stem" develop from suspension-load sedimentation in response to the creation of vortices at either end. The small diameter of the experimental stem strongly influences the development of these vortices and the resultant mode of sediment deposition. The large diameters of the *Taxodium* logs and most Carboniferous specimens examined permit flow through the cavity. Differences in hydrological pressures at either ends of the stem are minimized or totally reduced. Because of the irregularities along the interior of the cavity, a reduction in flow velocity within the cavity results in the deposition of laminated mud without wedge structures. This is the initial depositional structure within Rex's (1985) glass stem, but it is impossible to know whether the horizontal basal bedform that developed would have continued to form from suspension load if a larger tube diameter had been used.

Suspension-load casting processes in fine-grained depositional environments are the result of multiple events, not a single depositional event. Rex's model (1985) assumes that suspension-load infilling results from a single depositional event. Although this may be partially true for bedload fillings (Degges and Gastaldo, in prep.), it does not apply to suspension-load casts. The model proposed by Rex (1985), then, is based on a very specific set of conditions that is not commonly encountered in the fossil record. The proposed mechanism is not considered applicable as a generalized model to explain most suspension-load infilled cavities.

CONCLUSIONS

1. Complex taphonomic mechanisms are responsible for the development of mud cast logs commonly encountered in Carboniferous and Holocene clastic swamps.
2. Physiologically hollowed (pith) or easily hollowed internal cavities may occur in trees of various systematic affinity. Hollowing by biological mechanisms may occur during life, as in some extant *Taxodium*, or after death. Hollowing after death contributes to the emplacement of the trunk onto the forest floor. The hollow central cavity then acts as a conduit for sediment-laden waters.
3. The resistance of the wood and bark tissues to rapid degradation maintains the integrity of the centralized cavity. It may take several hundred years for a tree, lying prostrate on the forest floor, to completely rot. During this time, sediment-laden flood waters will be introduced into the swamp.
4. The horizontal, parallel bedding of the infilling mud is caused by suspension-load deposition over a period of time. The casting represents deposition from multiple overbank flood events. Deposition may be either the result of the recession of flood waters or hydrodynamic mechanisms. Mud subaerially exposed within the cavity can be the site for accumulation of a litter mat. This mud may also undergo surficial oxidation.
5. Coalified compression assemblages found within Carboniferous specimens represent a litter accumulation that was rapidly buried. Leaf litter mats are common in Holocene "incipient casts." The occurrence of these fossils may suggest the relative frequency of severe overbank flooding.
6. Alluvial mud within the hollowed log may provide a substrate for infaunal invertebrates, especially in the Holocene example. No evidence has been found, to date, to document similar infaunal activity in Carboniferous swamps. The level of ecological development of terrestrial infaunal invertebrate communities, similar to those of the Present, does not appear to have evolved by the Carboniferous.
7. The experimental model proposed by Rex (1985) for suspension-load casting is not applicable to fine-grained clastic stem fills. It is based on a very specific set of conditions that are not commonly encountered in the fossil record.

ACKNOWLEDGMENTS

The authors would like to thank C.W. Degges, D.S. Felton, A.C. Waters, and L.D. Eklund (Swamp Goddess) for assistance in the field; Dr. A. Rushing and M.W. Peebles for their assistance with the SEM; Auburn University School of Veterinary Medicine Radiology Department for assistance with the X-radiographs; Dr. R.B. Cook for interpretation of XRD patterns, and T. Jones for her assistance with the photography. The PI would like to thank Dr. M.H. Scheihing, ARCO Exploration, for the donation of his box coring device, and Mr. B. Beall, Curatorial Assistant, for access to the collections at the Chicago Field Museum. This project was supported by NSF EAR 8618815 to RAG.

REFERENCES

BLATT, H., MIDDLETON, G. and MURRAY, R., 1980, Origin of Sedimentary Rocks: Prentice-Hall Inc., Englewood Cliffs, N.J., 634 p.

CROCKER, D.W., and BARR, D.W. 1968. Handbook of the crayfishes of Ontario. University of Toronto Press, Toronto, Ontario, 158 p.

DIMICHELE, W.A., 1981, Arborescent lycopods of Pennsylvanian age coals: *Lepidodendron* with description of a new species: Palaeontographica B, v. 175, p. 85–125.

DIMICHELE, W.A., and DEMARIS, P.J., 1987, Structure and dynamics of a Pennsylvanian-age *Lepidodendron* forest: Colonizers of a disturbed swamp habitat in the Herrin (No. 6) Coal of Illinois: PALAIOS, v. 2, p. 146–157.

GASTALDO, R.A., 1986a, Implications on the paleoecology of autochthonous Carboniferous lycopods in clastic sedimentary environments: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 53(2/4), p. 191–212.

GASTALDO, R.A., 1986b, An explanation for lycopod configuration, 'Fossil Grove' Victoria Park, Glasgow: Scottish Journal of Geology, v. 22, p. 77–83.

GASTALDO, R.A., 1987, Confirmation of Carboniferous clastic swamp communities: Nature, v. 326, p. 869–871.

GASTALDO, R.A., 1988. A Conspectus of Phytotaphonomy *in* DIMICHELE, W.D., and WING, S.L., eds. Methods and Applications of Plant Paleoecology: Notes for a Short Course: Paleontological Society Special Publication, v.3, p. 14–28.

GASTALDO, R.A., 1989, Preliminary observations on phytotaphonomic assemblages in a subtropical/temperate Holocene bayhead delta: Mobile Delta, Gulf Coastal Plain, Alabama: Review of Palaeobotany and Palynology, v. 58, p. 61–83.

GASTALDO, R.A., submitted, Earliest evidence for helical crown configuration in Carboniferous trees: Journal of Palaeontology.

GASTALDO, R.A., GIBSON, M.A., and GRAY, T.D., in press, An Appalachian-sourced deltaic sequence, northeastern Alabama: Biofacies-lithofacies relationships and interpreted community patterns: International Journal of Coal Geology Special Issue, Peat and Coal: Origin, Facies, and Coalification.

GROW, L. and MERCHANT, H., 1980, The burrow habitat of the crayfish, *Cambarus diogenes diogenes* (Girard): The American Midland Naturalist, v. 103, p. 231–237.

MCBRIDE, E.H., and BURGESS, L.H., 1964, Soil survey of Baldwin County, Alabama: U.S. Department of Agriculture Soil Survey Series 1960, v. 12, p. 1–112.

PFEFFERKORN, H.W., FUCHS, K., HECHT, C., HOFMANN, C., RABOLD, J.M., and WAGNER, T., 1988, Recent geology and taphonomy of the Orinoco delta—Overview and field observations: Heidelberger Geowissenschaftliche Abhandlungen, Band 20, p. 21–56.

REX, G.M., 1985, A laboratory flume investigation of the formation of fossil stem fills: Sedimentology, v. 32, p. 245–255.

SCHEIHING, M.H., and PFEFFERKORN, H.W., 1984, The taphonomy of land plants in the Orinoco Delta: A model for the incorporation of plant parts in clastic sediments of Upper Carboniferous age in Euramerica: Review of Palaeobotany and Palynology, v. 41, p. 205–240.

SMITH, W.E., 1987, Genesis and function of fluvial elements of the Mobile-Tensaw River "delta": Geological Society of America, Abstracts with Program, v. 19, p. 130.

STOUT, J.P., LELONG, M.J., DOWLING, H.M., and POWERS, M.T., 1982, Wetland habitats of the Alabama coastal zone. Part III. An inventory of wetland habitats of the Mobile-Tensaw River Delta: Alabama Coastal Area Board Technical Report, v. 81–49A, p. 1–25.

TAYLOR, T.N., 1981. Paleobotany: An introduction to fossil plant biology: McGraw-Hill Inc., New York, 589 p.

WNUK, C., 1985, The ontogeny and paleoecology of *Lepidodendron rimosum* and *Lepidodendron bretonense* trees from the Middle Pennsylvanian of the Bernice Basin, Sullivan County, Pennsylvania: Palaeontographica B, v. 195, p. 153–181.