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Taphonomic and sedimentologic characterization of roof-shale floras

Robert A. Gastaldo
Department of Geology, Auburn University, Auburn, Alabama 36849-5305
Hermann W. Pfefferkorn
Department of Geology, University of Pennsylvania, Philadelphia, Pennsylvania 19104-6316
William A. DiMichele
Department of Paleobiology, National Museum of Natural History, Washington, D.C. 20506

ABSTRACT

Roof-shale floras have been a major source of data for the understanding of Carboniferous vegetation. Early debate on their origin centered around the question of whether these megafloral assemblages are autochthonous or allochthonous. In these discussions, the sedimentological context in which the preserved fossil assemblage (taphoflora) occurred was largely ignored. W. C. Darrah saw the complexity of these issues, presented helpful starting points for further investigations, and influenced the thinking of the next generation. This chapter characterizes the sedimentological and taphonomic features of a spectrum of roof-shale floras. There are three levels at which the preservation of plant parts can be viewed: (1) early taphonomic processes and earliest diagenesis can destroy or preserve plant parts in a given clastic depositional setting; (2) those plant parts that are preserved can be autochthonous, parautochthonous, or allochthonous in relationship to their original place of growth; (3) with respect to a peat layer (coal bed), the overlying clastic material can be deposited in a continuous transition, after a short temporal break (discontinuity), or after a significant hiatus of time. Characterization of roof-shale floras must take into consideration the sedimentological interpretation of the associated lithologies, the stratigraphic sequence, and the taphonomic processes involved in their formation. Characterization is essential before such floras can be used in higher-level interpretations, such as paleoecological reconstructions.

INTRODUCTION

A majority of all late Carboniferous adpression assemblages (taphofloras) are found as roof-shale floras, those preserved in the rock stratum overlying a coal seam. Many authors over the past nearly 100 years have attempted to clarify the relationships of these fossil assemblages to the bounding strata. In some instances these assemblages are genetically related to the underlying coal bed and represent the final phases of peat accumulation (for example, Scott, 1978; DiMichele and DeMaris, 1987) or thanatocoenoeses of peat swamp forest (death assemblages resulting from burial [for example, Demko and Gastaldo, 1992]). In other instances, these assemblages bear little or no genetic relationship to the underlying coal bed (for example, Peppers and Pfefferkorn, 1970; Baird et al., 1985).

The fossil floras under consideration have been variously called compression-impression floras, adpression[1] floras, fossil-plant asssemblages, megafloral assemblages, or taphofloras. We will use several of these terms interchangeably depending on the aspect of the fossil flora that we want to emphasize. The

*[1]Adpression—A plant fossil specimen showing a mixture of compression (plant parts compressed by sediment where some original or chemically altered plant tissue is still preserved) and impression (an imprint of the fossil plant on sediment or rock surface) states. Modified from Shute and Cleal (1987).

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term *roof-shale flora* expresses the stratigraphic position of a plant-bearing bed above a coal seam but contains no taphonomic information in itself, as we will demonstrate in this chapter. Roof rocks themselves can be siltstones or sandstones, even though shales are most common. Adpression floras occur not only in roof rocks but also in floor rocks, often referred to as underclays (Scheihing and Pfefferkorn, 1984; Wnuk and Pfefferkorn, 1987), or in beds that have no direct or indirect relationship to coal beds. However, roof-shale floras are more common and represent a very specific setting in which the relationship to the coal bed begs for an explanation.

Paleobotanical diversity characterized the scientific interests of the late William C. Darrah (1909–1989). During the more than 50 years of his career he investigated topics ranging from pure systematics (for example, Darrah, 1940, 1969), developmental paleobiology (for example, Darrah, 1941), and plant evolution (Darrah, 1938) to plant biogeography (for example, Darrah and Bertrand, 1933; Darrah et al., 1937), plant biostratigraphy (for example, Darrah and Barlow, 1972; Lyons and Darrah, 1979), and what would now be categorized as plant taphonomy (Darrah, 1969, p. 66–71, and written communications to Gastaldo, 1986, 1987). The one question that Darrah pursued throughout his career, though, focused on the interpretation and significance of roof-shale floras, those fossil-plant assemblages from which he collected a multitude of data. Through his teaching and writing he influenced the thinking of several members of the next generation of paleobotanists, including the first and second authors of this chapter.

Earlier interpretations of roof-shale assemblages were generally based upon observations restricted to limited in-mine and outcrop exposures. Too often explanations to account for their genesis were made without regard to complex sedimentological and stratigraphical relationships that may have played a significant role in development of the fossil deposits. The purpose of this contribution is to summarize the spectral characteristics of roof-shale floral assemblages found in the late Carboniferous. It is beyond the scope of this chapter to discuss in detail the large-scale roles that tectonics, eustacy, climate, and sometimes volcanism play in the development of such assemblages (see Gastaldo et al., 1993).

PREVIOUS INTERPRETATIONS OF ROOF-SHALE FLORAS

As is the case in many scientific discussions, early debate on the origin of roof-shale floras was polarized. The polarity of modern interpretations traces its origin to debate during the late nineteenth and early twentieth centuries concerning the autochthony or allochthony of coal itself. Dawson (1878) described in detail the section in Joggins, Nova Scotia, that contains many upright tree trunks of substantial height. Therefore, he advocated at least for these specific occurrences an autochthonous origin and could prove it beyond reasonable doubt. White and Thiessen (1913) brought a similar set of observations from the American coalfields and advocated the autochthonous origin of most coal beds and at least of those roof rocks containing erect trunks. However, most localities do not show such clear evidence. In an attempt to settle the debate about autochthony versus allochthony, Stevenson (1911a, 1912, 1913) reviewed the arguments of the opposing sides, detailed transport processes of plant detritus and its accumulation, surveyed the Carboniferous stratigraphy of the Appalachian basin and the occurrence of preserved plant material, and elucidated the relationships of clastic strata bounding the coal deposits. He presented a discussion that utilized the preservational state of vegetation within the coal-bearing sequence to argue for autochthony of the coal (Stevenson, 1913). Part of his discussion focused on the roof rock. He noted that a variety of lithologic types may overlie a coal bed, ranging from black shale to sandstone and even conglomerate (Stevenson, 1913), and described the variety of plant fossil assemblages encountered in these rocks, ranging from erect cast trees to fragmentary detritus. In some instances, he attempted to compare the preservational mechanisms to modern analogues. Stevenson did not take a dogmatic position but rather concluded that the plant-part compositional and preservational state of the assemblage in the roof shale could be used as an indicator of autochthony or allochthony. He stated that erect trees are found only in deposits on which there was never more than a shallow cover of water (Stevenson, 1913, p. 114).

Stevenson's arguments present a range of possible developmental processes for roof shales and the associated floras. In contrast, Davies (1929) took a position at one end of the spectrum. He asserted that the vegetational elements found within roof-shale assemblages directly reflected the plants that comprised the underlying coal bed and that spatial variation in species diversity and quantity of plant material represented the heterogeneity of the original mire community. Hence, he presumed that roof-shale assemblages were all autochthonous. North (1935), on the other hand, argued that the material was not *in situ* and that nearly all specimens originate in topogenous lows, and the prevailing wisdom asserted that drifted material overlay coal seams. Therefore, the systematic affinity of plants in the roof shale was not necessarily identical to those found in the underlying coal. Roof-shale floras, then, could only have been comprised of allochthonous megafloral elements, and preserved plants represented vegetation sampled from a variety of habitats. Autochthony was proposed for all well-preserved roof-shale floras by some authors in Germany (Keller, 1931; Draegert, 1964); others discussed various origins but emphasized hypoautochthonous occurrences (Josten, 1961; Hartung, 1966—equivalent term to parautochthonous as used herein).

The natural world rarely operates at either extreme of a polarized spectrum, and Gothan and Gimm (1930) and Havlena (1961) recognized that both autochthonous (flöznah, lycopsid-dominated assemblages) and allochthonous (flözfern, fern- and pteridosperm-dominated assemblages) associations could be identified above a variety of coals within the same sedimentary basin. Similarly, Oshurkova (1974) recognized autochthonous and allochthonous assemblages (phytoryctocoenoses of lepidodendrid stems and pteridospermous rachises, respectively) in central Kazakhstan, and Scott (1979) reported them from Great Britain. Attempts at identifying the gradient between these extremes have been alluded to (for example, Gastaldo, 1987), but never, to our knowledge, characterized.

Darrah (1969) summarized his experience and thinking about geological problems in the interpretation of fossil floras, including questions of paleoecology and plant taphonomy. He made the point that sedimentology had been neglected. He called compression floras coal floras and interpreted most of them as allochthonous or what we would call parautochthonous. However, he also pointed out the complexity of these interpretations and how provisional his interpretation had to be. The strength of his discussion was the recognition of what had to be done and in which direction research had to go. We present in this chapter a short summary of work and ideas that resulted from studies of the nature he suggested.

Jennings (1986) has taken a different approach to the question. Acknowledging that roof-shale floras may differ in quantitative composition from coal-ball floras and palynofloras, he argued (p. 304) that the plant fossils in the roof shales of the Mississippian and Pennsylvanian represent primarily the same taxa that comprise the coal itself. This is certainly true to a certain degree of taxonomic resolution. The overlap between coal-ball floras and adpression floras is very high at the family or genus level, as any survey of the literature will reveal. However, it appears that many of the species known from compressions do not occur in coal balls. This is most notably the case for medullosan pteridospermous foliage (see DiMichele et al., 1985) and for many small ferns and other pteridosperms. Other groups, such as the arborescent lycopsids, clearly had lineages ecologically and evolutionarily centered in mires. The edaphic differences between peat and mineral substrates undoubtedly underlie these distributional patterns. By generalizing the argument to one of broad taxonomic similarity, Jennings overlooked the importance of understanding the depositional environment of roof shales to the interpretation of the provenance of the flora and the degree to which peat-forming floras can be understood by studies of adpressions. The latter is basically a paleoecological, not a taxonomic, issue.

THE CHARACTERIZATION AND CLASSIFICATION OF ROOF-SHALE FLORAS

Terrestrial clastic deposits overlying coals display a variety of sedimentological features that directly reflect the processes responsible for their accumulation. The presence or absence of plant parts within these rocks is a direct function of processes operating prior to, during, and after deposition. The understanding of a roof-shale flora requires the observation of the small-scale stratigraphy below and above the plant-bearing bed, the sedimentologic characteristics of these rocks, and the taphonomic characteristics of the plant fossils themselves. We can approach the taphonomic-sedimentologic-stratigraphic interpretation at three different levels of processes or relationships: (1) The preservation or nonpreservation of plant matter in the stratum, (2) the relationship between the place of growth of the flora and the site of its preservation, and (3) the relationship of the flora in the overlying sediment to the underlying peat. As discussed below, these three levels are largely, but not in every case, independent of each other.

Preservation or nonpreservation can depend on processes operating in the environment itself or during early diagenesis (Fig. 1). As paleobotanists we tend to concentrate on cases in which preservation took place. Barren roof rocks are frequently observed but rarely reported because of the absence of megascopic plant parts. Sedimentological structures characteristic of these roof shales run the gamut from pin-stripe laminations to megaforms, depending upon the depositional setting of the terrestrial clastics. Often these roof shales are massive mudstone in which primary sedimentary structures are absent, but cases have been reported where tidal rhythmites overlie the coal bed (Scott, 1979; DiMichele and Beall, 1990; Gastaldo et al., 1990). Palynomorphs and dispersed cuticles may be recoverable from macerations, but visually observable detritus is missing from this roof-shale type.

We recognize three basic categories of taphofloras if we want to express the relationship between site of growth and location of burial: autochthonous, parautochthonous, and allochthonous fossil-plant assemblages. The principal processes and features are summarized in Figure 2 and Table 1, and examples are discussed below. This classification is valid for any

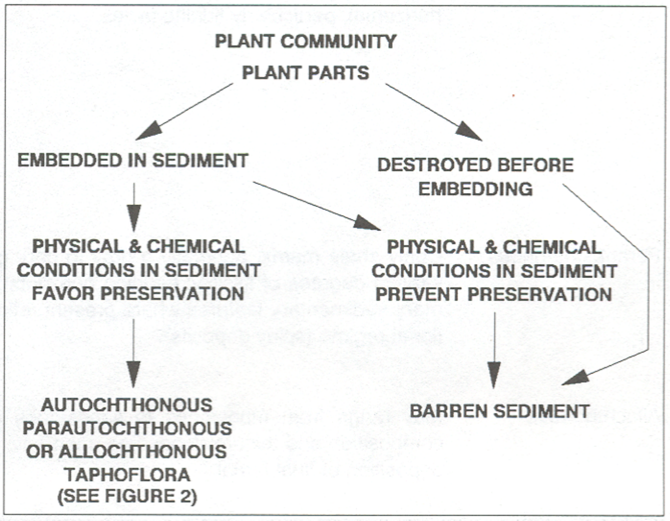

Figure 1. Pathways leading to the preservation or nonpreservation of plant parts in clastic sediments. Barren sediments in general and barren roof shales in particular are common. Phytodebris and/or palynomorphs may or may not be present in barren sediments.

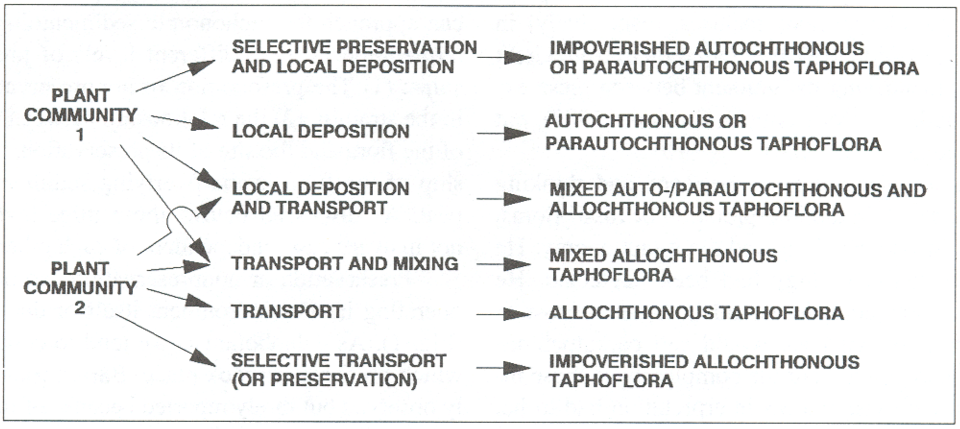

Figure 2. Generalized schematic diagram of the transformation of plant communities into fossil-plant assemblages (taphofloras). Only the major and most common processes are illustrated, demonstrating some of the factors that must be understood before roof-shale floras can be interpreted. These taphonomic processes must be combined with knowledge of the sedimentological system to come to a credible interpretation of roof-shale floras.

TABLE 1. SEDIMENTOLOGIC AND PLANT-TAPHONOMIC CHARACTERISTICS OF ADPRESSION FLORAS ADDRESSING THE RELATIONSHIP BETWEEN SITE OF GROWTH AND DEPOSITION OF THE PLANT PARTS FOUND

	Sedimentological Characteristics	Paleobotanical Characteristics
Autochthonous	**Catastrophic:** Massive mudstone up to several meters thick; gray to light gray in color; primary sedimentary structures generally absent; where present are large scale. **Noncatastrophic:** Coaly shale matrix; black, carbonaceous, fissile. Bedding horizontal, particularly tidalite facies.	**Catastrophic:** Erect trees of various systematic affinity; *Calamites* may show regenerative features; less robust vegetation subhorizontal to subvertical orientation; forest floor litter concentrated; Gaussian size distribution restricted to basal ± 10 cm; adpressions and partial casts. Second canopy litter accumulation may be present at top of event deposit. **Noncatastrophic:** Erect trees of various systematic affinity may or may **not** be present; less robust vegetation horizontal; aerial axes represented by vitrain bands, partial to completely filled casts; higher proportion of woody detritus with foliage rarely preserved; distance between bedded litters increases up section.
Parautochthonous	Coaly shale matrix, generally a gray to dark gray shale, varying degrees of fissility; bedding horizontal; other primary sedimentary features where present reflect depositional regime (splay deposits).	Horizontally bedded detritus of varying systematic affinity, mostly composed of pteridosperm, pteridophyte, and sphenophyte parts; concentrated assemblages with well-preserved detail; generally Gaussian size distribution of plant parts; may be up to several meters in thickness.
Allochthonous	May range from mudstones to sandstones of varying composition and texture depending upon environment of deposition of final burial.	Plant detritus of varying size attributes and preservational features; mixture of floral elements sometimes of isolated pinnules, pinnae, seeds, branchlets, etc.; floras may be impoverished or enriched. Plant "hash" common.

plant-bearing deposit, but we will consider it from the viewpoint of roof-shale floras.

Stratigraphic categories have been used in evaluating the specific relationship between a plant-bearing roof shale and the underlying coal (Table 2; Fig. 3). Sedimentation can be continuous while changing from organic to clastic, a short temporal break can occur between the cessation of organic sedimentation and the onset of clastic deposition, or a hiatus of significant duration can occur.

Autochthonous taphofloras

Autochthonous fossil-plant assemblages are those in which remains are preserved at the death site of the organism or the site where parts were discarded either by physiological or trauma-induced loss (Bateman, 1991; Behrensmeyer and Hook, 1992; Gastaldo, 1992a). The genesis of these assemblages may be the result of catastrophic burial (event deposition) or slow but regular sedimentation; for instance, on a daily basis with less than a millimeter deposited each day (Table 1). The taphonomic aspect of the preserved plant matter is quite distinct in these two cases (Figs. 3A, 3B). Roof-shale floras may clearly represent the last vestiges of peat-swamp vegetation in cases where no diastem separates the roof shale from the coal bed. The plants are preserved *in situ,* and observed floral assemblages often consist of erect trees rooted within and preserved for some distance above the coal bed. Prostrate and subhorizontal plants and plant parts that represent not only the canopy but also understory vegetation are found to occur between the erect vegetation (DiMichele and DeMaris, 1987; DiMichele and Nelson, 1989; Gastaldo, 1990a). These include complete stems, leaves, aerial branches, and reproductive structures and their propagules.

Several taphonomic features allow for the delimitation of this subcategory of autochthonous peat-swamp assemblages if burial resulted from catastrophic high-discharge, low-frequency flood events (Demko and Gastaldo, 1992). Erect trees are surrounded and cast by gray mudstone in which primary sedimentological structures generally are rare (if present they are a function of the relative proximity of the buried forest to the channel[s] transecting the area). Erect lycopsids, calamites, and tree ferns may be preserved for heights up to 8 m (Gastaldo, 1986, 1990b). Particular taxa, especially *Calamites* sp., show signs of regenerative behavior after burial (Gastaldo, 1992b). Understory vegetation may be preserved in place, within the basal 10 cm, and is found generally in a subvertical to subhorizontal orientation, cross-cutting the encasing rock. The preserved megaflora is heterogeneous with respect to plant-part types and plant-part sizes and is generally taxonomically diverse (ecological parameters will constrain the degree of heterogeneity or homogeneity within the floral assemblage; DiMichele and Nelson, 1989). Most plant parts are preserved as concentrated adpressions, although incompletely filled mud-cast logs may be present (Gastaldo et al., 1989). The incomplete casting of these hollow voids is the result of a very short duration (on the order of up to several weeks) of available suspension-load sediment within the area. Litter may be deposited on top of the flood deposit when erect buried trees undergo canopy part abscission, forced reproduction, or death (Gastaldo, 1987, 1990a). Consequently there may be a barren interval between the buried forest floor and the final litter layer produced.

Slow but continuous burial of a peat swamp may occur due to local/regional subsidence and/or peat compaction generating accommodation space. This may result in the slow death and drowning of mire taxa, on occasion accompanied by a transition to a different assemblage adapted to a mineral substrate (clastic swamp; Wnuk and Pfefferkorn, 1987). Characteristics of this assemblage include the presence of discrete bedded detritus within a coaly shale matrix (dark gray to black, fissile and carbonaceous) or within the basal portion of tidalite sequences. The thickness of the lithology reflects the depth of generated accommodation space (usually >0.5 m). Erect trunks may occur on hummocks, whereas isolated hori-

TABLE 2. SEDIMENTOLOGIC AND PLANT-TAPHONOMIC CHARACTERISTIC OF ROOF-SHALE FLORAS ADDRESSING THE RELATIONSHIP OF THE CLASTIC BED IN WHICH THE PLANTS ARE PRESERVED AND THE UNDERLYING COAL BED

Continuous sedimentation	Sedimentation changes from organic to clastic; bony coal and carbonaceous shales may occur; boundary could be sharp in some cases.	Paleobotanical assemblages may be autochthonous, parautochthonous, or allochthonous; however, only in this setting can floras be found that are autochthonous with respect to underlying coal.
Short temporal break in sedimentation (discontinuity)	Chemically induced alteration of sediments above coal; flooding of swamps provides impetus for reaction of peat with overlying water column; includes pyritization and authigenic cementation by siderite.	Paleototanical assemblages may be autochthonous, parautochthonous, or allochthonous with respect to site of clastic deposition; assemblages are always unrelated to underlying coal.
Significant hiatus often with erosional event	Sedimentary environments may represent any of the settings mentioned in Table 3; however, channel deposits are frequently typical for this setting.	Paleobotanical assemblages may be autochthonous, parautochthonous, or allochthonous with respect to site of clastic deposition; assemblages are always unrelated to coal.

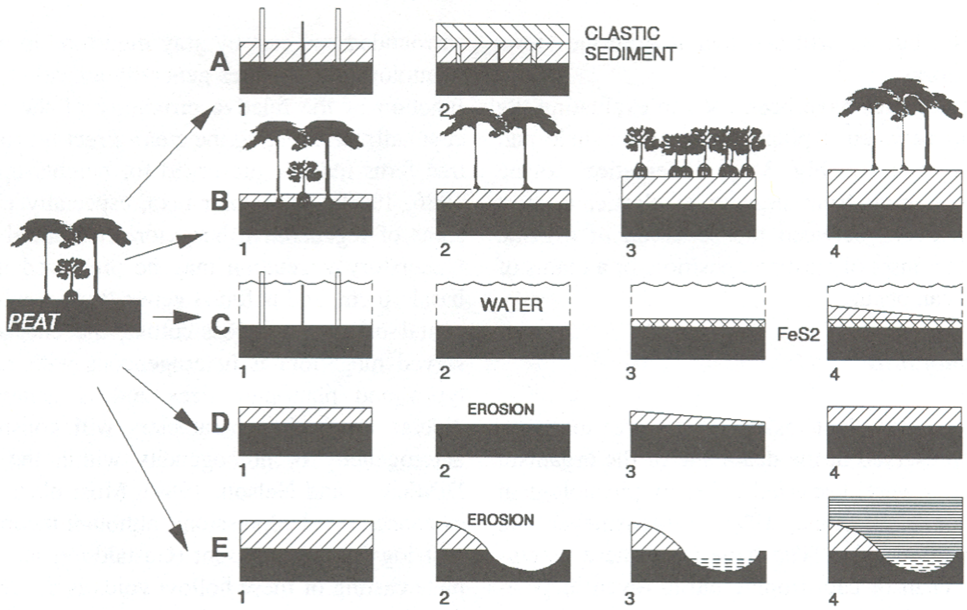

Figure 3. Schematic diagram of some of the processes responsible for roof-shale formation over peat. The illustrated processes must be considered in conjunction with the information in Figures 1 and 2 and Tables 1 and 2 to interpret a particular roof-shale flora. **A,** Catastrophic burial by clastic sediment of forest growing on peat results in plant death and decay above sediment interface (A1) followed by subsequent burial and infilling (A2). **B,** Mire forest is subjected to low rate of clastic sedimentation with part of the litter layer preserved; stumps decay and may be infilled (B1); subsequent colonization and continued sediment accretion may result in successive communities rooted in mineral substrates (B2–B4). **C,** Mire is permanently flooded without accompanying sediment input (C1); tree death and decay result, leaving only fallen flattened stems in the upper peat layer (C2); water circulates through the peat; uppermost part of peat is oxidized, pyritized, phosphatized, or otherwise mineralized (C3); clastic sedimentation occurs at a later point in time (C4). In this scenario, water chemistry may range from fresh, to brackish, to marine. **D,** Erosion removed sediment cover down to the peat (D1–D2); unknown interval of time passes before new sediments are deposited (D3–D4); earlier sediment may remain on peat in irregular lenses. **E,** Erosion removes sediment and cuts into the peat body (E1–E2); new sediment is deposited (E3–E4); earlier sediment may remain present in irregular lenses or may be absent.

zontal trunks may be preserved either as discrete thick vitrain bands, shale-cast logs with periderm structure preserved as enveloping vitrain bands, or elliptical to circular mud-cast logs. The proportion of woody axial material may be higher than that of foliage (Scott, 1978; Wnuk and Pfefferkorn, 1984; DiMichele and DeMaris, 1987) as a result of long-term exposure at the sediment surface and/or secondary rooting. Litter is concentrated with resistant plant parts, particularly cuticles, which are often abundant. Plant-part distribution along bedding planes may display features reflecting physical processes that acted upon the site during accretion (for example, Wnuk and Pfefferkorn, 1987).

Parautochthonous taphofloras

Parautochthonous floral assemblages are those composed of remains that are transported from the death or discard site but reside within the original habitat (Bateman, 1991; Behrensmeyer and Hook, 1992). These are the classic roof-shale floras derived from vegetation that colonized slightly higher topographies (for example, channel margins and levees) adjacent to the clastic depositional setting in which the plant parts were preserved (see Scott, 1978, 1979; Scheihing and Pfefferkorn, 1984; Pfefferkorn et al., 1988). Plant parts may have been introduced by a variety of traumatic (overbank flooding and splay development; Gastaldo, 1987, demonstrates the relationship) or physiological mechanisms. Preservation of the predominantly pteridophyte-pteridosperm and herbaceous sphenophyte assemblages typically is excellent (for example, Scott, 1978; DiMichele et al., 1991). The assemblages are often concentrated (sensu Krasilov, 1975) in horizontally bedded gray shales or silty shales. Concentration does not imply an overlapping of individual plant parts as one would find in autochthonous floras (representing true forest-floor litter). Parts are often discretely isolated spatially from each other. Plant parts generally reflect no specific abiotically generated orientation pattern. The total thickness of a parautochthonous accumulation may be up to a few meters (depending upon available accommodation space).

Allochthonous taphofloras

Allochthonous floral assemblages represent the other end of the transport spectrum from autochthonous assemblages. Such remains have been moved from the site of death or discard and moved out of their original site of habitat (Bateman, 1991; Behrensmeyer and Hook, 1992). Deposition of this plant detritus may occur many kilometers away from the actual site of growth (for example, Gastaldo et al., 1987; Gastaldo and Huc, 1992), and the detritus is emplaced over peat bodies that have been subjected to relative change in elevation. This usually follows a hiatus in sedimentation following the termination of peat accumulation. Plant parts are generally a mixture of floral elements originating from a variety of habitats naturally sampled from along the transect of a feeder channel (for example, Scott and Chaloner, 1983; Peppers and Pfefferkorn, 1970; Pfefferkorn, 1979; Scheihing and Pfefferkorn, 1984). Plant parts are commonly found dispersed in the sediment and represent isolated pinnules, pinnae, seeds, branchlets, and woody detritus (for example, Scott, 1977). The depositional site may be any one of many found within depositional settings in fluvial plains, coastal plains, deltas, or estuaries (Table 3). The sedimentological features characterizing these settings, then, would be reflected in the lithology (for example, Walker and James, 1992). The thickness of sediments in which allochthonous megafloras may accumulate may be greatly dependent upon available accommodation space generated by compaction, tectonics, or a rise in base level. Allochthonous floras may be impoverished by selective transport (for example, Mosbrugger, 1989; Cunningham et al., 1993) or by sorting of taxa through hydrologic processes. Conversely, floras may be enriched by the amalgamation of taxa sampled from a variety of ecological settings (for example, Darrah, 1969, 1972; Pfefferkorn, 1979). In general, plant parts exhibit a variety of size extremes and preservational features that are dependent upon the freshness of the plant part at the time of emplacement on the sediment-water interface and subsequent physical processes that may have mechanically fragmented this detritus (see Spicer, 1989; Gastaldo, 1992c). Where physical destruction has been taken to the extreme, plant hash assemblages predominate (Gastaldo, 1994).

TABLE 3. PRINCIPAL DEPOSITIONAL ENVIRONMENTS AND THEIR SUBENVIRONMENTS COMMONLY ENCOUNTERED ABOVE COAL BEDS

Major Environments	Subenvironments or Deposits
Fluvial channel	Bedload sands and lags; point-bar sediments; longitudinal and lateral bar sands*; bank deposits and slumps*.
Natural levee	Levee sediments*; crevasse splay channels*; crevasse splay levee*; crevasse splay shield*; clastic backswamp*.
Flood plain	Intermittently "dry" flood plain; flood plain lake; oxbow lake.
Coastal plain	Flood deposits*; tidal deposits under various salinities*; tidal channels*; wetlands*; estuarine and lagoonal deposits*; tidal flats*; beach sands, washover fans.
Delta	Interdistributary bay; delta-front sheet sand; those listed with an asterisk above.
Nearshore marine	Tidal flats; barrier-bar sands; tidal channels.

The categories discussed so far apply to the fossil-plant assemblage and are applicable to roof-shale and other adpression floras. The categories that follow address the stratigraphic relationship between the clastic plant-bearing bed and the underlying coal bed. This relationship has to be recognized in order to interpret taphonomy and origin of the flora properly. These categories can be combined with the other categories discussed above in many different combinations, but it must be kept in mind that some combinations are logically impossible and others rare.

Continuous sedimentation across peat–to–clastic-sediment boundary

Continuous sedimentation is a precondition for the preservation of an autochthonous or parautochthonous peat flora in the overlying clastic sediment. Therefore, this case has been discussed under the heading autochthonous taphofloras. In the two cases discussed below where short or long interruptions in the sedimentation occur, the taphoflora in the clastic material cannot be autochthonous with respect to the underlying coal.

Short temporal break in sedimentation between peat and clastic sediment

We recognize this category based on a very sharp but otherwise conformable boundary at the coal-clastic interface. This happens where a relative rise in base level floods the swamp and kills the peat-forest vegetation (Fig. 2C). The resulting flood plain lake or lagoon may not receive any sediment for several years. This break may be accompanied by chemical reactions of the peat with the overlying water column, which may result in precipitation of a thin layer of pyrite, phosphate, or carbonate within the very top of the peat body. Some coal-ball occurrences may have a similar origin (Scott and Rex, 1985). Other pore water reactions may result in the development of phosphatic-sideritic nodules (Woodland and Stenstrom, 1979; Curtis, 1977). After some time sediment will start to reach the site, often in the form of the distal ends of crevasse splays. The type of paleobotanical assemblage found under these circumstances in the roof shale varies considerably and has no relationship to the underlying peat.

However, the flora may represent one or several subenvironments of the same larger depositional system (i.e., coastal plain, fluvial plain, or delta).

Significant hiatus between peat and clastic sediment

Although it can be argued that the presence of any terrestrial clastic lithology above a coal bed is, in itself, representative of a disconformity, we refer to this category those cases in which a clastic unit has been secondarily emplaced on top of a peat body after erosion of the original overlying sediments (Figs. 3D, 3E). These floral assemblages may appear to be similar to other roof-shale floras (Fig. 3D) or may have been deposited within channels of various dimensions that have eroded down to the top or even into the peat (Fig. 3E). Hence, they represent material that has been introduced above the peat some time after relative base-level rise. The contact between the plant-bearing lithology and the coal bed is unconformable. The plants in these deposits can represent a different depositional system and even a different chronostratigraphic stage from that of the peat.

Often these sediments are channel deposits, and this particular setting requires some further discussion. Because the coal is a saturated flaccid accumulation, it may act as a localized trap for bedload-transported detritus, and basal-lag accumulations therefore develop. Other in-channel litter deposits may develop in a variety of bar structures. Channelization may be a function of fluvial (see Ferm and Horne, 1979; DeMaris et al., 1979) or tidal activity (Gastaldo et al., 1993), and sedimentary structures will reflect the prevailing physical depositional conditions (see Walker and James, 1992). Plant assemblages are generally composed of the most resistant aerial parts, including trunks and branches, which may be compressed into vitrain bands or cast in the prevailing bedload sediment. Depending upon the physical processes operating in the channel, macroscopic plant detritus may occur as concentrated bedded litter or drapes overlying cross beds. Where degraded and physically fragmented detritus has been redistributed into channels via fluctuating water conditions, plant parts may occur as plant hash.

DISCUSSION

It is evident that a wide variety of complex interactive taphonomic and sedimentologic processes affect the genesis of roof-shale floras. The diversity of interacting factors results in an assortment of assemblage characters. Local and/or regional physical processes ultimately result in the rise of the relative position of base level over short (for example, rapid subsidence in response to tectonics) or longer time intervals (for example, prolonged subsidence in response to tectonics, sea-level rise, or sediment compaction). This relative rise in water level inversely relates to a relative descent in the elevation of the peat-forming forest. Where the mire forest has developed a planar geomorphic form, the entire region would then be placed in jeopardy of increased flooding by low-frequency and high-magnitude floods (Demko and Gastaldo, 1992). Where ombrogenous peat swamps exist (McCabe, 1984), the once-elevated interior portions of these swamps may or may not be placed in jeopardy of being flooded, which may explain the distribution of some coal partings. Once a peat-accumulating forest has been placed at risk, it is only a matter of time before catastrophic burial may occur. Pfefferkorn et al. (1988) noted in the Orinoco delta, Venezuela, that during the recorded 150-year flood (regarded by them as a moderate-frequency and moderate-magnitude flood), longitudinal bars (up to 5 m in height) had been deposited on top of levees that are up to several meters above stream-channel waters. This means that sediment normally restricted to bedload transport is carried in suspension load, and normal suspension-load sediment is transported into forested areas adjoining these channels, a consequence of water rise on the order of greater than 10 m. Flood waters regress from the forest over a period of about a few weeks or months. Under circumstances that may generate the 1,000- or 10,000-year-magnitude flood, an increased sediment load would remain resident in the waters overlying the forests for longer periods of time. This would result in the catastrophic burial of the forest by alluvium, leaving only those trees erect that exhibit the greatest structural integrity. Evidence for such floods has been well documented in the Carboniferous (for example, Liu and Gastaldo, 1992a).

Base-level changes occurring over the longer term can be related to tectonics in intramontane basins and a combination of tectonics and eustatic changes in paralic basins. This type of change may slowly subject the peat swamp to incursion not only be fresh to brackish waters (the presence of orbiculoid and/or lingulid brachiopods in roof shales is indicative of such settings) but also by marine waters. Slow rise in base level accompanied by intermittent overbank sedimentation or freshwater tidal deposition (Scheihing and Pfefferkorn, 1984) provides the setting in which wetland vegetation not only can survive but also can contribute canopy parts to the accumulating sediment in which it is growing. Concentrated plant litter accumulating within mud may ultimately be preserved as an organic-rich shale.

The above scenarios are not intended to imply that mud-cast erect vegetation can only be formed under a subsidence and catastrophic burial scenario, and we do not intend to imply that roof shales with well-bedded autochthonous litter can only be formed under a slow base-level rise or by localized peat compaction. These are merely the most conspicuous of simple mechanisms to explain autochthonous roof-shale floras. It is possible that mud-cast erect vegetation could have been formed within a setting controlled by longer-term processes (for example, DiMichele and DeMaris, 1987). But such interpretations cannot be made subjectively based solely upon the characteristics of the fossil-plant assemblage. A thorough understanding of the sedimentological characters associated with the assemblage is essential. As fluvial, coastal, or deltaic plain settings are heterogeneous with respect to geomorphological features at any one point in time, so are the laterally correlative potential depositional sites that may preserve plant litter. It is imprudent to place an unequivocal interpretation on the genesis of an autochthonous megafloral assemblage, or in fact any assemblage, without the sedimentological context within which it is preserved.

Most Carboniferous biostratigraphy is based upon those megafloral assemblages interpreted by us to have been preserved as parautochthonous accumulations. Such assemblages include a high proportion of pteridophyte and pteridospermous elements that typically inhabited slightly better drained peat or clastic soils in coastal wetland settings (for example, Gastaldo, 1987; Wnuk and Pfefferkorn, 1984). Their presence may indicate some transport into a site with higher preservation potential. Their mere presence alone, though, does not justify the interpretation of parautochthony. Wnuk and Pfefferkorn (1984) and Gastaldo (1990b) have demonstrated that there may be significant numbers of autochthonous pteridophyte and pteridospermous elements in a particular shale. It is therefore important to understand not only lateral lithofacies distribution of the roof shale but also the sedimentological features in it. The taxonomic diversity, size of preserved plant parts, and plant-part disposition in the rock cannot provide a definitive answer as to whether the assemblage is parautochthonous.

The character of an allochthonous assemblage relates to the mode of transport and emplacement of the plant detritus in the depositional environment that has become established over the former peat-forming swamp. The degree to which plant parts are recognizable is dependent upon several factors that include the freshness of the part when introduced to the water column (traumatic loss or dehiscence following dysfunction), the residency time of the part in the water column and the resistance to degradation of any particular plant part (Gastaldo, 1992c), the physical processes to which the parts have been subjected (Gastaldo, 1994), and the biogeochemical conditions within the substrate. Plant parts are normally evenly distributed throughout the deposit; as new material is transported into the depositional environment, it settles at the sediment-water interface and is incorporated through continued burial. In some instances, plant detritus may be reentrained and transported to beaches of lakes, lagoons, or the ocean, where it may accumulate as detrital peat. Reentrainment and mechanical fragmentation of allochthonous plant detritus result in the development of plant hash often found distributed along bedding surfaces.

Megafloras deposited in sediments that follow a short time of nondeposition represent an inherent change in geochemical conditions that reflect a perturbation within the depositional setting. For example, an increase in activity of sulphate-reducing bacteria and preservation of plant parts by pyrite signal a widespread change in concentrations of pore-water oxygenation. This change may be induced by one or more chemical processes operating in the shallow subsurface, at the sediment-water interface, or within the water column. The same can be applied to nodule floras found throughout the Midcontinent. The development of such assemblages reflects a postdepositional alteration of the chemical environment that may, or may not, have been induced by the introduction of the phytoclasts. It does imply, though, not only that the organic substrates were in place prior to the chemical alteration but also that they had not yet been subjected to lithification.

Fossil-plant assemblages preserved in sediments deposited on the peat bed only after a long hiatus are often found in small, localized deposits that represent their introduction above the peat through erosion of the overlying sediment. These floras may be allochthonous (detritus transported into the accumulation site), parautochthonous (contributed from vegetation growing along the margins of the channel), or autochthonous (representing vegetation growing in a shallow or abandoned channel). An understanding of the megaflora in sedimentological context within these channel deposits is the only way that interpretations can be resolved between the three possible accumulations. In instances where the flora is regionally distributed, its presence may be in response to local subsidence or regional transgression accompanied by shoreface erosion. In the latter instance, ravinement processes may contact the underlying peat, and this detritus may become part of the ravinement bed (Liu and Gastaldo, 1992b).

Many roof shales lack megafloral remains. Although rarely discussed, the lithologies that comprise this category are varied, representing a spectrum of depositional settings that provide information about basinal history. The absence of megafloral elements may be due to the hydrological regime in which the sediments were deposited, geochemical conditions (Eh and pH relationships) that prevailed during accumulation that may have prevented plant-part preservation, or extended distance of the depositional setting from a source area. Often, those roof shales considered to be barren are designated as such only because concentrated megafloras are not preserved. It is common, though, to find scattered bits and pieces that may provide information not readily available in other roof-shale types (Tiffney, 1990).

CONCLUSIONS

Roof-shale floras have been, and continue to be, a primary source of information concerning Carboniferous vegetation. Interpretations as to what these floras actually represent have often sought simplistic absolutes ranging from autochthony to allochthony. An evaluation of the types of roof-shale floras encountered and reported in the Carboniferous results in the recognition of several categories that fall into three different groups. There is preservation resulting in a taphoflora versus nonpreservation resulting in a barren roof shale. Depending on the amount of transport plant parts experience before embedding, one can distinguish autochthonous, parautochthonous, and allochthonous fossil-plant assemblages. Finally one can distinguish the relationship of the peat bed and the overlying clastic sediments. Deposition can be continuous but changing from organic to clastic or discontinuous with a short interval of nondeposition, or a long hiatus can intervene that could include an erosional event.

In addition, we understand today that we are dealing with two broad groups: those that represent the final vegetation of the mire forest that formed the underlying peat and those from lowland mineral substrate habitats that were deposited in the same site after the cessation of peat formation. Roof-shale floras that exemplify the former are autochthonous or parautochthonous assemblages with regard to the underlying peat representing the final vegetational stand of the peat-forming forest. In essence, this is a geologically instantaneous picture of the forest that has undergone either catastrophic burial and death or death from edaphic stress followed by slow burial. The final peat-swamp forest may be gradually replaced by clastic swamps if colonization occurs within the mineral substrate, resulting in a succession of autochthonous clastic-swamp accumulations in the shale above the coal bed. These clastic accumulations have no genetic relationship to those established in the peat substrate. Their establishment may occur over a relatively short stratigraphic distance (<1 m) or over several meters of section. Roof-shale floras that do not represent the final mire vegetation may rest conformably or unconformably on the peat. Megafloras that are conformable were deposited after a short break in sedimentation. Plant parts are locally introduced via flooding and splays into standing bodies of water that are resident above the peat body. The transported plant material may come from a local source (parautochthonous) or from outside the immediate surroundings of the site of deposition (allochthonous) or both. Plant parts that have been subjected to bedload transport and/or mechanical degradation will result in the development of "plant hash" assemblages (sensu Gastaldo, 1994) distributed along bedding planes. Where these overlying terrestrial clastic sediments are colonized, wetland plant communities may develop, but these bear no relationship to the underlying peat-swamp community. Roof-shale floras preserved within channels that have eroded into an underlying peat body are unconformable and may represent the range of allochthonous to autochthonous assemblages. Again, though, these floras bear no direct relationship to the underlying peat-swamp vegetation.

Differentiation of any category of roof-shale floras must be made in conjunction with the sedimentological features of the lithologies in which they are preserved. Roof-shale floras cannot be interpreted in a sedimentological void, and an understanding of the depositional context of a preserved flora is essential before attempts can be made at interpreting its significance.

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