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Erect Forests Are Evidence for Coseismic Base-level Changes in Pennsylvanian Cyclothems of the Black Warrior Basin, U.S.A.

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ABSTRACT

Examination of the plant taphonomic character and sedimentological processes responsible for preservation of an in situ, erect forest above the Pennsylvanian Blue Creek coal of the Mary Lee coal cycle, Alabama, provides evidence for rapid generation of accommodation space by coseismic subsidence. Standing vegetation is preserved at least to 4.5 m (15 ft) in height above the coal and includes lycopsids, regenerative calamites, tree ferns, and seed ferns (pteridospermous gymnosperms); the forest-floor litter is preserved as an adpression assemblage directly above the coal. Sediments entombing the standing trees, burying both the peat mire and forest-floor litter, and casting the erect vegetation consist of rhythmically bedded tidalites. Neap-spring-neap tidalite patterns indicate that entombment occurred on the order of a few decades, whereas burial of the mire and forest-floor litter happened on the order of weeks, if not days. Comparison with documented Holocene rates of eustatic and tectonic base-level changes indicates that eustatic processes alone cannot account for the generation of the accommodation required to provide a basis for the sedimentologic and taphonomic characteristics of the assemblage. Instead, coseismic subsidence of very high magnitude is determined to be the mechanism responsible for preservation. Hence, erect forests buried by estuarine tidal deposits provide evidence for rapid coseismic basinal subsidence. These criteria can be used to identify similar coseismic subsidence events beginning in the middle Paleozoic and provide constraints on the magnitude of event-driven base-level change in various basinal regimes.

INTRODUCTION

Various models and mechanisms have been proposed to account for cyclicity in the sedimentary character of marine and continental rocks in the Upper Carboniferous of Euramerica, and the rubric of these controversies is reviewed elsewhere (see Pashin, 2004; Cecil, 1990; Klein and Kupperman, 1992; Klein, 1994). There is a general agreement that the generation of accommodation space to allow for cyclothem deposition is eustatic-driven (Dewey and Pitman, 1998), and timescales under which such fluctuations in sea level are compatible with those that are orbitally mediated (e.g., Dickinson et al., 1994). However, it has been argued that both allocyclic and autocyclic processes can operate in cyclothems (Klein and Willard, 1989; Klein and Kupperman, 1992), and the sedimentary signatures encapsulated therein can provide clues to decipher which process is responsible for a particular part of that stratigraphic interval (Demko and Gastaldo, 1996). New data from the Blue Creek coal in the Mary Lee coal zone, Black Warrior Basin, Alabama, are now available that provide a basis on which tectonic versus eustatic changes in base level can be evaluated and identified in a single cyclothem. Hence, these data can be used not only for constraining the magnitude of tectonic base-level change, but also for providing criteria that can be used to identify similar coseismic coastal subsidence in other parts of the stratigraphic record.

Because of the discontinuous nature of the stratigraphic record, basinal subsidence rates have been calculated on several gross time intervals. These rates generally are presented as modeled subsidence curves plotting change-in-depth vs. stratal age (e.g., Stephenson et al., 1992) or as calculations to reflect meters of displacement per million years or centimeters per millennium (e.g., Fortuin and de Smet, 1991). Although several authors (e.g., Thommeret et al., 1981; Bloom and Yonekura, 1985) have suggested that localized basin subsidence and uplift occur in a spasmodic manner, and published data support this assertion (e.g., Plafker and Rubin, 1967; Plafker and Savage, 1970), little evidence has been provided, to date, allowing for identification and demonstration of these processes in the rock record. The purpose of this contribution is to provide such data and the rationale for identifying earthquake-induced base-level changes of at least 4.5 m (15 ft) in a foreland basin setting.

MARY LEE COAL ZONE

The Mary Lee coal zone is one of nine basinwide economic coal-bearing cycles identified in the Pottsville Formation (Langsettian = Westphalian A; early Pennsylvanian) of the Black Warrior Basin, a triangular foreland basin located between the Appalachian and Ouachita orogenic belts (Thomas, 1988) (Figure 1). Pashin (2004) has characterized the basin as a faulted homocline dipping southwestward toward the

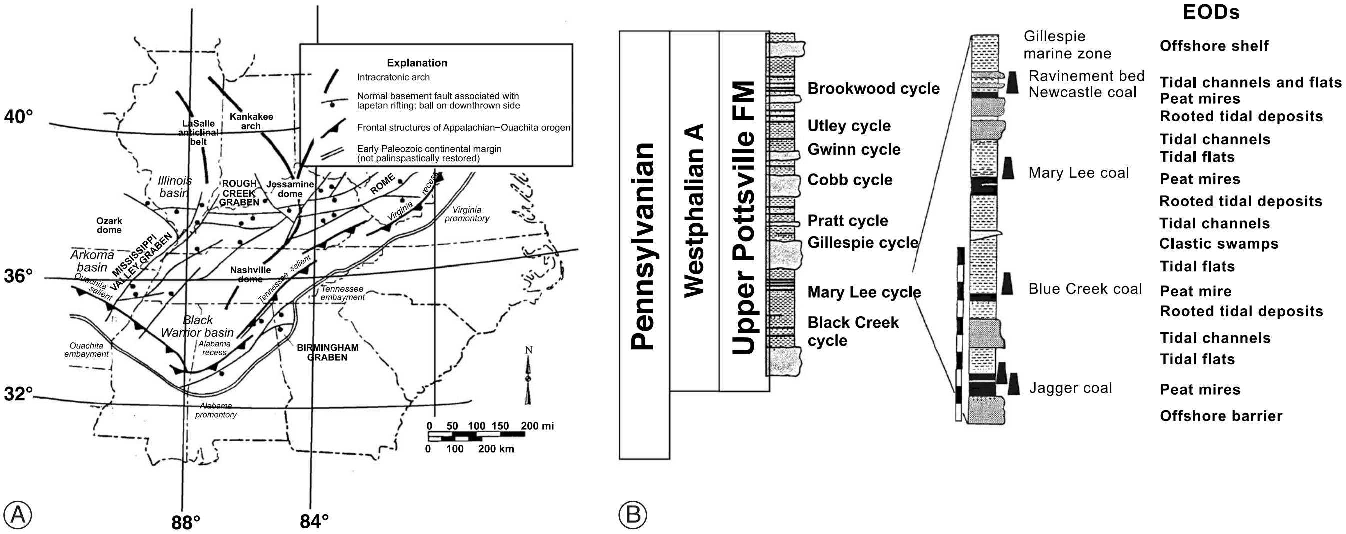


Figure 1. (A) Regional tectonic setting of the Black Warrior Basin (after Thomas, 1988) and (B) generalized stratigraphic column of the upper part of the Carboniferous section in the Black Warrior Basin. The Mary Lee coal cycle is expanded, illustrating the stacking pattern of siliciclastic deposits and coal, with interpreted environments of deposition (EOD) indicated (after Gastaldo et al., 1990).

Ouachita orogen, with the frontal folds and faults of the Appalachian system superimposed on the southeastern margin. Thirteen cycles in this sequence (Pashin, 1994a, b) are bounded by ravinement surfaces formed during the maximum rate of sea level rise (Liu and Gastaldo, 1992a), which can be identified not only in outcrop and core (Demko and Gastaldo, 1996), but also in geophysical well logs (Pashin, 1994a). Hence, these have been considered by Gastaldo et al. (1993) and Pashin (1994a, 2004) coincident with the genetic sequence boundaries of Galloway (1989) and the transgressive maximum flooding surfaces of Van Wagoner et al. (1990).

Gastaldo et al. (1991, 1993) defined the Mary Lee coal zone as consisting of the Jagger, Blue Creek, Mary Lee, and Newcastle coal seams (the latter a coal-seam split restricted to northwest Walker County, Alabama) underlain by a thick fine- to medium-grained sublitharenite informally called the "Jagger bedrock" sandstone. The coal zone crops out more than at least a 1000 km^2 (386 mi^2) area as surface mine highwalls (now mostly reclaimed), road cuts, and natural exposures. Mine highwalls extended laterally for several kilometers, having allowed for the development of a three-dimensional perspective of facies architecture (Demko, 1990a). Demko and Gastaldo (1996) described the vertical succession of facies in the following sequence of environments (Figure 1):

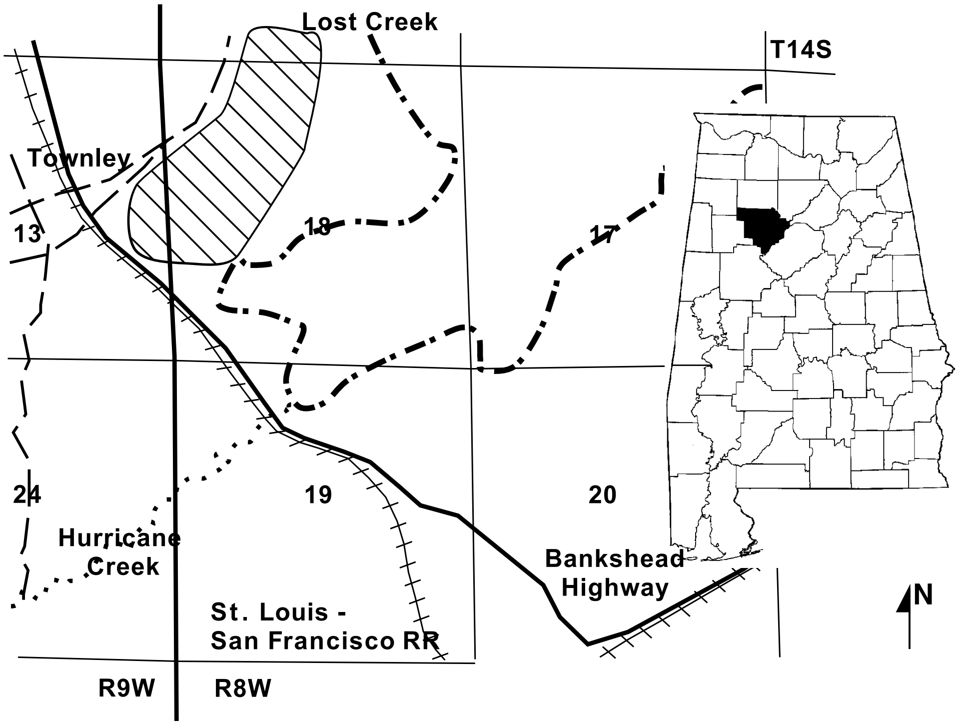
1) Tide-influenced shelf to lower shoreface as recorded in the Jagger bedrock sublitharenite. This sandstone is characterized by large-scale trough cross-stratification organized in large dune and sand-wave megaforms organized as shore-parallel bars, the tops of which have undergone incipient pedogenesis.
2) Discontinuous coastal peat mires, clastic swamps (Gastaldo, 1987), and tidal mud flats represented by the Jagger coal and overlying clastic facies. The Jagger coal occurs as isolated, lenticular bodies that may be as thick as 2.3 m (8 ft) (in troughs of the underlying Jagger bedrock sandstone) or less than 0.1 m (0.3 ft) (overlying megaform crests) across a distance less than 1 km (0.6 mi). A persistent carbonaceous shale parting splits the Jagger coal, which is low in sulfur (0.9–1.0%) and moderate in ash (10–15%; Barnett, 1986), and erect lycopsid trees are preserved in situ. The overlying interval is characterized by a pinstripe laminated, fine-grained sandstone-and-siltstone sequence as much as 9 m (30 ft) thick in which neap-spring tidal cyclicity has been recognized (Demko et al., 1991).
3) The Blue Creek coal is the most extensive coal bed in the basin, known in the subsurface close to the Appalachian structural front and westward into Mississippi and in outcrop exposure in northwest Walker County. This coal marks the position of lowstand in the coal zone and is overlain by aggrading clastic swamps (Demko and Gastaldo, 1992). The overlying sedimentary sequence is variable, including heterolithic pinstripe laminated siltstones; entisols with in situ stigmarian axes and rootlets, overlain by erect lycopsids, calamites, pteridosperms, and pteridophytes; and fine-grained sandstones in channel-form geometries, the tops of which also are rooted and on which the Mary Lee mire formed.
4) The peat mire deposits of the Mary Lee coal are overlain by tidal-influenced fluvial and deltaic deposits. The Mary Lee coal is split in the northwestern part of Walker County into a rider seam, the Newcastle coal, with an intervening sequence of channel-form sandstone bodies and mudstone lithologies that show sedimentary structures characteristic of tidal-influenced regimes (Gastaldo et al., 1990). Overlying the coals are shallow, wide-sheet, and channel-form bodies of fine sandstone and siltstone displaying rhythmic bedding cycles. These occur in accretionary bars wherein pinstripe and flaser-bedding structures have been identified (Liu and Gastaldo, 1992a, b). This interval was interpreted by Liu (1990) to represent primarily fluvial environments that experienced some tidal influence.
5) The Newcastle coal and/or the channel-form fine sandstones and siltstones are truncated by a planar erosional surface that can be traced in outcrop and the subsurface for greater than 1800 km^2 (695 mi^2). Liu and Gastaldo (1992a) described the sedimentological and paleontological variability of the thin overlying lithologies, interpreting these rocks as a condensed section, the result of ravinement processes. The overlying marine sediments are part of the Gillespy cycle.

Hence, this sequence reflects terrigenous sedimentation along a low-gradient coastal plain in one fourth- or fifth-order cycle (Pashin, 2004), at frequencies associated with classical Pennsylvanian cyclothems.

Blue Creek Mire

The thin (0.3–0.5 m [1–1.6 ft]), continuous Blue Creek coal is a very low-sulfur (0.6–0.7%) and ash (13–14%; Barnett, 1986) bright-banded coal with a

Figure 2. Index map of Alabama on which Walker County is indicated (black), and location of the Drummond Brothers, Cedrum mine in which the present study was conducted (SW 1/4, T14S, R8W, Sec. 18, U.S. Geological Survey, Townley, Alabama, 7.5′ quadrangle).



small fusain component considered to be degradofusinite (C. Eble, 1991, personal communication). Winston (1990a) determined that the coal was composed of 49% lycophyte trunks, 36% rootlets, 9% pteridosperm, 5% fern, and 1% degraded biomass in samples taken from the Cedrum mine in Townley, Alabama. Preserved at the coal-clastic contact is an autochthonous assemblage consisting of (1) erect lycophyte (Gastaldo, 1990), calamite (Gastaldo, 1992), pteridosperm, and pteridophyte axes; and (2) an exceptionally well-preserved adpression fossil-plant assemblage, with elements lying parallel or slightly inclined to bedding. Fluvial overbank processes were implicated to account for the burial of this autochthonous assemblage (Gastaldo, 1990). The plant fossils are surrounded and cast by the heterolithic siltstone-sandstone lithology in which neap-spring tidalite deposition has been recognized (Gastaldo, 1992).

Materials and Methods

The data presented herein are based on concurrent studies in the Drummond Brothers Company's Cedrum mine in Townley, Alabama (Townley, 7.5-ft quadrangle, Sec. 7, T14S, R8W, and Sec. 18, T14S, R8W; Stevanoviç-Walls, 2001; Ware, 2001) (Figure 2). Observations were made, and samples were collected primarily during 1999–2000 in a 1.36-km (0.8-mi)-long surface mine (western margin, N 33E49′ 868″, W 87E25′384″; eastern margin, N 33E49′380″, W 87E24′942″), although reported specimens and observations also originate from other mining operations in the area (e.g., Gastaldo et al., 1990; Gastaldo, 1992). A photomontage of the highwall was compiled, allowing for recognition of large-scale features above the Blue Creek coal. In addition, thin sections were made of the 4–5-cm-thick layer of the forest-floor litter in what was field identified as mudstone, 0–10 cm (0–4 in.) directly above the coal seam. Oriented thin sections are perpendicular to bedding and were examined using standard petrographic techniques to evaluate the sediment character between litter-created bedding planes, the presence of primary sedimentary structures, and other features that may reflect depositional processes responsible for the preservation of the forest.

Siderite concretions identified in ground thin sections were analyzed for carbon and oxygen isotopes to characterize the sedimentological regime under which they formed. Billets were subsampled with a fine drill at approximately 5-mm (0.2-in.) intervals along six siderite nodules, with each microsample label indicating coal, collection site, and sample number, and subsample in the transect (e.g., sample BC VI 1Aa indicates the Blue Creek coal [BC], sample site VI, the first sample from the site [1], first part of sample 1 [A], and the consecutive microsamples [a–h]). Powdered samples were reacted with five drops of 100% phosphoric acid at 80°C in a Finnigan Kiel II automated reaction system for approximately 30 min. The CO$_2$ produced was analyzed on a Finnigan MAT 251 isotope-ratio mass spectrometer in the Department of Geology and Geophysics at Texas A&M University. For calibration to the Peedee belemnite (PDB) standard, the carbonate standard NBS-19 (δ^{13}C = 1.95‰, δ^{18}O = −2.20‰) was used (i.e., Vienna PDB).

Table 1. Taxonomic composition of canopy, subcanopy, and ground cover/liana plants preserved in the Blue Creek mire.

Canopy	*Subcanopy*	*Ground Cover/Liana*
Lepidodendron aculeatum	*Pecopteris arborescens*	*Alloiopteris* sp.
Lepidodendron obovatum	*Cardiopteridium* sp.	*Diplothmema* sp.
Lepidophloios laricinus	*Eremopteris Rhodea type*	*Lyginopteris hoeninghausii*
Sigillaria elegans	*Eremopteris* sp.	*Palmatopteris furcata*
Sigillaria ichthyolepis	*Eusphenopteris lobata*	*Sphenophyllum emarginatum*
Sigillaria scutellata	*Sphenopteris brongniarti*	*Sphenophyllum cuneifolium*
Calamites cisti	*Alethopteris* cf. *valida*	*Sphenopteris* cf. *schatzlarensis*
Calamites suckowi	*Alethopteris lonchitica*	*Sphenopteris herbacea*
Artisia	*Neuralethopteris elrodi*	*Sphenopteris pseudocristata*
	Neuralethopteris pocahontas	
	Neuralethopteris schlehani	
	Neuralethopteris smithsii	
	Neuropteridium sp.	

Plant Taphonomy of the Blue Creek Forest

Adpression and Prostrate Cast Assemblage

A concentrated accumulation (sensu Krasilov, 1975) of exclusively aerial plant parts is preserved directly above the Blue Creek coal in the first 5–10 cm (2–4 in.) of siliciclastics (this bed may be as thin as 3 cm (1.2 in.) and as thick as 15 cm (6 in.), depending on the locality). The thickness of the plant-fossil assemblage at any particular site is controlled spatially by the underlying topography of the Jagger sandstone (Demko, 1990a, b). The plant debris consists of randomly oriented trunks, stems, and branches of canopy and subcanopy elements (lycophytes and calamiteans); juvenile and mature foliage of canopy elements and their reproductive cones either terminally attached to branches or disseminated (lycophytes and calamiteans); mature foliage of subcanopy taxa and occasional bare rachial elements (pteridophytes and medullosan pteridosperms), as well as reproductive structures (pollen organs, fruits, and seeds); and ground cover/liana forms consisting of small-diameter axes with attached leaves [sphenophylleans, lyginopterid pteridosperms, medullosan and callistophytalean(?) pteridosperms, and pteridophytes; Table 1]. The plant parts are preserved primarily as adpressions, which Shute and Cleal (1987) have defined as any plant fossil showing a mixture of compression states (plant parts compressed by sediment where some original or chemically altered tissue is still preserved) and impression states (an imprint of the fossil plant on sediment or rock surface).

Fossil-plant detritus collected from the coal-siliciclastic interface is not preserved well and commonly appears as an organic coalified film without morphological or cellular detail. When viewed in thin section (Figure 3A), this material is similar in petrographic character to the underlying and contiguous coal. Leaves and small-diameter branches appear as individual, isolated vitrinite laminae, whereas some evidence exists for charcoalification (fusain) and cellular preservation of larger-diameter (>1 cm [>0.4 in]) axial debris near the uppermost interface of the coal (Figure 3A). Commonly, it is impossible to determine the systematic affinity of the plant below the major plant group.

Well-preserved plant fossils occur less than 1 cm (0.4 in.) above the upper coal contact. Thick, robust aerial stems are preserved mainly by coalification and commonly exhibit some three-dimensional topography in the rock. Prostrate lycophyte and calamitean trunks as much as 1 m (3 ft) in compressed width (equivalent to the original tree diameter; Rex and Chaloner, 1983; Thomas, 1986) generally are preserved slightly convex, unless they occur as casts, in which case they may exhibit a variety of cross-sectional lenticular shapes dependent on the quantity of siliciclastic fill (Gastaldo et al., 1989). Juvenile lycopsid trunks (sensu Kosanke, 1979) have been found lying flat with spirally attached leaves (*Lepidophylloides* sp.), each of which may be as much as 1 m (3 ft) in length. Smaller-diameter axes, such as medullosan trunks that are as much as 15 cm (6 in.) in compressed width, also may be preserved prostrate in three dimensions or may crosscut the entombing lithology and, in a few instances, extend into the overlying, plant-barren beds.

Leaves are found in a variety of stages of completeness and preservation. Entire fronds (central bifurcate

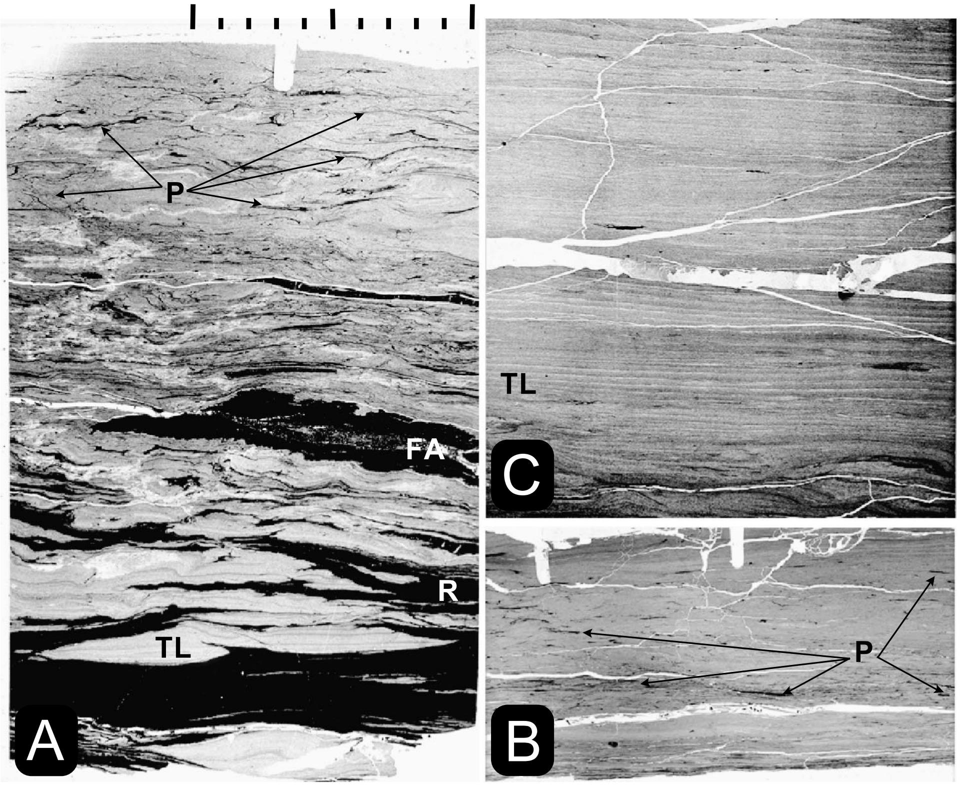


Figure 3. Thin sections across the upper contact of the Blue Creek coal and overlying sediments. (A) Thin section in which the Blue Creek coal (BCC) and overlying forest-floor litter can be seen to be buried by thin laminations of very fine sandstone/coarse siltstone and siltstone/mudstone. A fusainized axis (FA) is near the top of the coal. (B) Thin section of the forest-floor litter wherein aerial plant parts, including rachial axes (R) and pinnules (P), define bedding planes. (C) Thin section of tidalite sequence overlying the forest-floor litter horizon. Scale for all photomicrographs is in millimeters.

or nonbifurcate rachis with attached lateral pinnae including pinnules), as well as frond fragments (entire pinnae or pinnae apices) and isolated individual pinnules (i.e., medullosan pteridosperms), coexist at all stratigraphic levels in the bed, preserving the assemblage. Irregardless of the completeness of the leaf (frond), pinnules from thin and delicate taxa (e.g., *Sphenopteris*), large, robust, and thick taxa (e.g., *Neuralethopteris*, *Alethopteris*), or small, robust, and thick taxa (i.e., *Lyginopteris*), all exhibit nondessicated features that include well-defined outlines that may be in three dimensions, distinct venation patterns, and in some cases, cuticles and cellular details. Additionally, pinnae of larger fronds commonly were found across successive stratigraphic levels, defining the bedding planes in those instances. In thin section, pinnules are encountered as coalified laminae that may be parallel or at some angle to bedding (Figure 3B).

The taphonomic character of plant detritus changes upsection into the more siliciclastic-rich interval overlying the coal, where there is a marked decrease in plant-part concentration. Here, the fossil assemblage is dispersed; there is a complete loss of all prostrate canopy and subcanopy axes, as well as any evidence of complete and partial leaves attributable to subcanopy taxa. Only occasionally are medullosan pinnules found preserved in rocks more than 10 cm (4 in.) above the concentrated assemblage, wherein they appear as isolated coalified laminae in thin section (Figure 3C). A concentrated, coalified plant assemblage may be encountered at the stratigraphic level that defines the uppermost limit of the erect trees (Demko and Gastaldo, 1996) (Figure 4).

Erect, In situ Trees

The standing forest is cast above the Blue Creek coal and consists of erect lycopsids (Gastaldo, 1990), calamites (Gastaldo, 1992), pteridophytes, and pteridosperms; no erect cordaitean axes have been encountered. Basal trunks of lycopsids, ranging from 0.20 to 0.95 m (0.7 to 3 ft) in diameter, are congruent with the top of the coal, and with stigmarian axes extending into the underlying mire. Subterranean axes and ''rootlets'' commonly are not cast by siliciclastics; instead, these are coalified and can be traced in the uppermost part of the coal bed when exposed prior to exploitation. Lycopsid trunks are cast by the same lithology responsible for entombing the trees (see below), and the bark tissues (periderm) have been coalified as a surrounding vitrain band. Individual trees are preserved for various heights above the Blue Creek coal, and the total height of any tree may be dependent on the underlying topographic relief of the Jagger bedrock sandstone (Demko and Gastaldo, 1996) or the exposure in the highwall. Individual trees range from less than 0.5 to more than 4.5 m (1.6 to >15 ft) in height (Figure 4), but the maximum

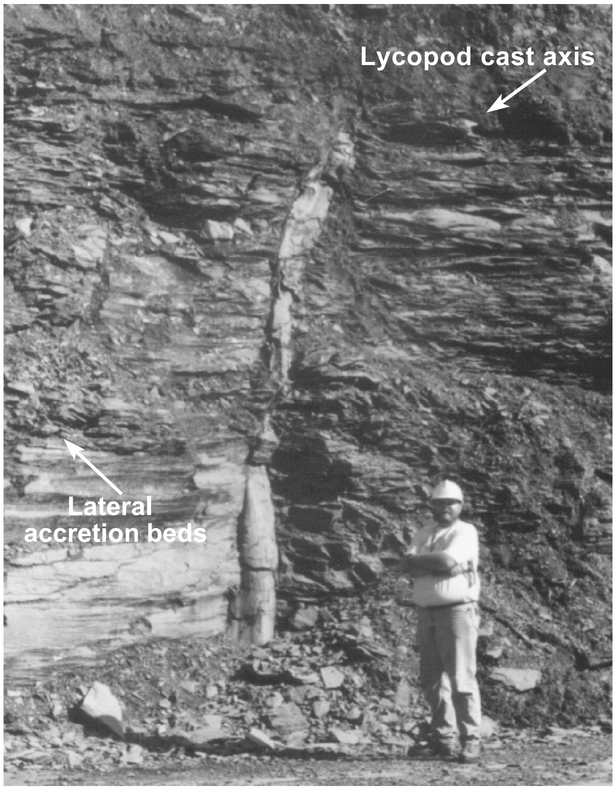


Figure 4. Erect, unidentifiable lycopsid at the Drummond Brothers mine, Townley, Alabama. (Sec. 24, T14S, R9W, Townley 7.5-ft quadrangle) extending 4.5 m (15 ft) above the Blue Creek coal. A siltstone-cast lycopsid axis (at arrow) can be seen at the stratigraphic level where the standing tree terminates, and lateral accretion beds onlap the tree (at arrow).

height recorded in any particular part of the mine represents the height to which all living vegetation was entombed. In most instances, lycopsids are not preserved perpendicular to the coal, but instead are at some slight angle from vertical. Most are typified by an exterior vertical fissuring, indicative of bark sloughing during diameter increase, making assignment to a specific taxon difficult. Average tree diameter in the Cedrum mine was reported to be 42 cm (17 in.) (Gastaldo, 1990).

Calamites are encountered as either isolated, erect pith casts or in small clusters. Most specimens are oriented at a slight angle from perpendicular to nearly 45° from vertical, and pith casts are surrounded by coalified aerial tissues (wood and bark). Several examples exist where individual plants have undergone regeneration following burial (Gastaldo, 1992), and in these cases, helically arranged roots that originated at buried nodes crosscut entombing primary bedding structures (Figure 5A). Piths are cast by the same lithology surrounding the aerial axes, and axes generally remain constant in diameter from the base to the top of the specimen, with a maximum observed diameter of 0.28 m.

It is unusual that both isolated, sparse ferns (pteridophytes) and seed ferns (pteridosperms) are encountered erect and cast above the coal. Several stems of *Psaronius* cf. *simplicaulis* (DiMichele and Phillips, 1977), a distichously branched tree fern, have been recovered that exhibit both external morphology and internal anatomy (Figure 6A) (in the absence of internal anatomy, specimens with these features would be assigned to *Megaphyton*; Pfefferkorn, 1976). Tree fern stems are as much as 9 cm (4 in.) in diameter and were at least greater than 2 m (6.6 ft) in height when excavated from the highwall, although it was not possible to recover an entire tree. Each specimen has U-shaped leaf scars arranged in two vertical rows on opposite sides of the stem along with adventituous roots directed geopedally. In addition, each stem also exhibits internal vascular trace architecture, with coalified conducting cells preserved in a siliciclastic matrix (Figure 6B, C). Pteridosperm axes are much thinner in diameter than all other erect vegetation, with maximum diameters approaching less than 10 cm (4 in.). They generally are found inclined at angles as much as 45° originating from the upper surface of the Blue Creek coal and may have adventituous roots directed geopedally. The axes commonly are compressed, with a minimum of sediment infill.

Sedimentology of the Blue Creek Forest

Based on field characterization, the forest litter is preserved in a mudrock, ranging from 3 to 15 cm (1 to 6 in.) in thickness, that is distinguished by numerous bedding planes created by the preferential orientation of the plant fossils. The lowermost 3–5 mm (0.1–0.2 in.) of the interval encompasses the top of the coal, is dark gray (N2) to black (N1), and consists of concentrated degraded organic matter. The remainder of the mudstone is light to medium gray (N3), appears to show no primary sedimentary structures in hand sample, and contains the bulk of identifiable adpressions. Depending on the site sampled, sideritic nodules with authigenically cemented plant material may or may not be present. Where present, siderite nodules are more concentrated directly above the coal and decrease in size and frequency upsection.

Isotope analyses of siderite nodules indicate that carbon ratios range from 6.04 to 9.96‰ and oxygen ratios range from −4.16 to −3.02‰ (Figure 7). High carbon isotopic values are diagnostic of formation in the zone of methanogenesis (Gautier, 1982; Moore

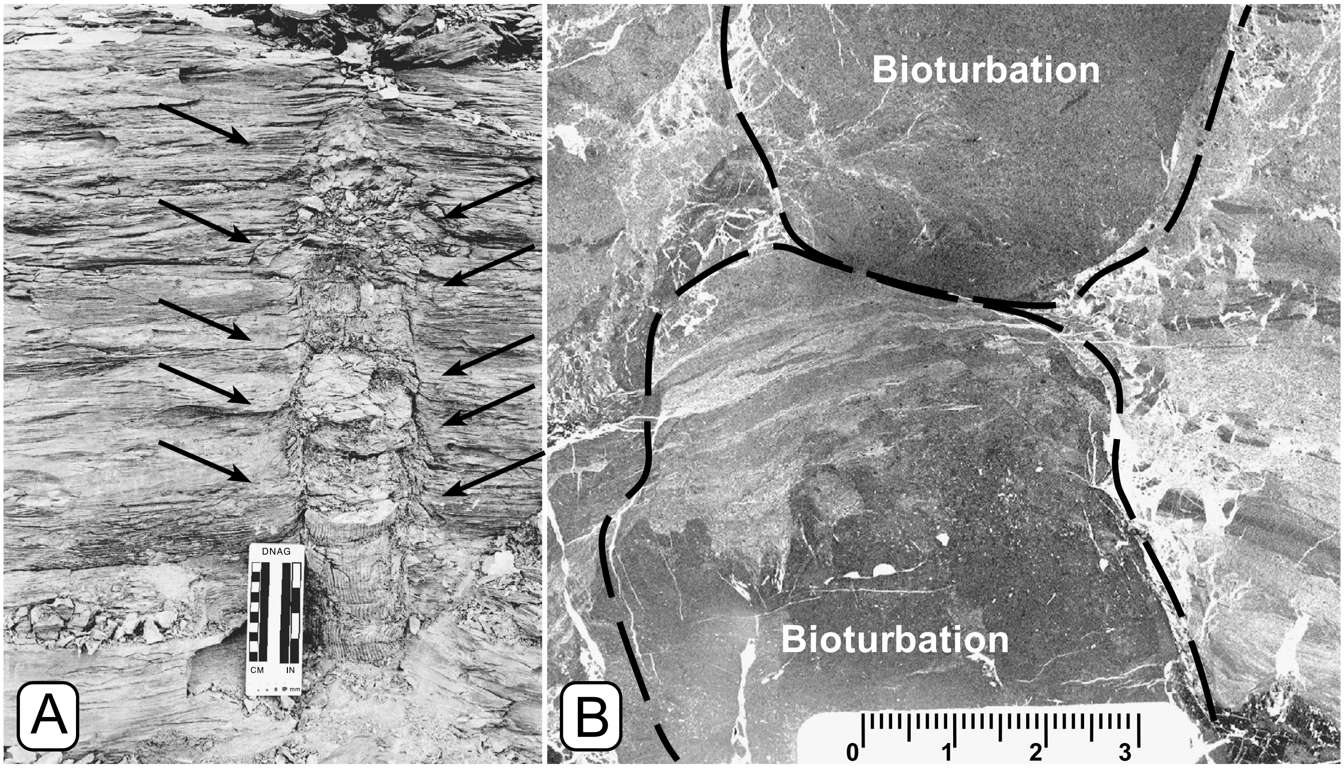


Figure 5. Erect, standing regenerated calamitean axis with secondary roots crosscutting tidalite sediments. (A) Standing axis at Coal Systems, Inc., Lost Creek mine (T13S, R9W, Sec. 33/38, U.S. Geological Survey, Nauvoo, Alabama 7.5-ft quadrangle; Demko and Gastaldo, 1992) with secondary rooting structures indicated at arrows, originating from the nodes of the aerial axis. Scale is 10 cm (3.9 in.). (B) Longitudinal section of pith cast in which tidalite deposits are displayed above and below zones of bioturbation. Dashed lines outline the longitudinally sectioned calamite axis (see Gastaldo, 1992). Rhythmites can be seen adjacent to axis in entombing sediments. Scale in millimeters.

et al., 1992), which in freshwater systems is accomplished primarily by acetate fermentation (Whiticar et al., 1986). The kinetic carbon-isotope fractionation associated with methanogenesis can produce $\delta^{13}C$ values as high as 10‰, which are within the range of values obtained. The high values found in the siderite nodules above the coal probably are caused by the abundant plant debris in the roof shale and high rates of methanogenesis associated with their preservation. However, because C3 plant carbon is isotopically light (~26‰), the $\delta^{13}C$ data reflect fractionation overprinting by bacterial methanogenesis instead of the original isotopic signature of the organic matter. Similar values of sideritic $\delta^{13}C$ have been reported in freshwater Holocene marshes of the Mississippi delta (Moore et al., 1992) and in a shale parting of the Foord coal seam, Nova Scotia (Zodrow and Cleal, 1999). The $\delta^{18}O$ data reflect isotope values consistent with nonmarine pore waters (Mozley and Wersin, 1992), and the small range in values is indicative of early diagenetic siderite precipitation. Additionally, depleted $\delta^{18}O$ values in sites II and V (Figure 7) correlate with what is interpreted as a "wetter" setting based on the ratio of *Sigillaria* to *Lepidophloios* debris. Gautier (1982) and Moore et al. (1992) interpreted similar data as representative of fresh pore-water environments. Hence, the sediment-laden waters responsible for burial and preservation of the forest were freshwater in origin.

Overlying the forest litter is a tidalite facies (Demko and Gastaldo, 1996) distinguished on the presence of pinstripe interlaminated, dark-gray to medium-gray (N3–N4) mudstone and very fine-grained sandstone (N7–N8). Laminations range from 0.1 to 3 mm (0.004–0.12 in.) in thickness, and silt-sized muscovite and sideritic mudstone clasts are minor constituents. Sandstone laminae thicker than 1 mm (0.04 in.) commonly are draped with silt- to sand-sized, coalified, comminuted plant detritus, which also may be found concentrated in the troughs of current ripple structures. Mudstone and sandstone laminations range in thickness throughout the interval in a pronounced cyclicity (Demko, 1990b). Primary sedimentary structures include (1) horizontal, parallel, bedding; (2) microscale cross-lamination; (3) tool marks; (4) rill marks; (5) rippled surfaces; (6) raindrop imprints; and (7) soft-sediment deformational features. Paleocurrent

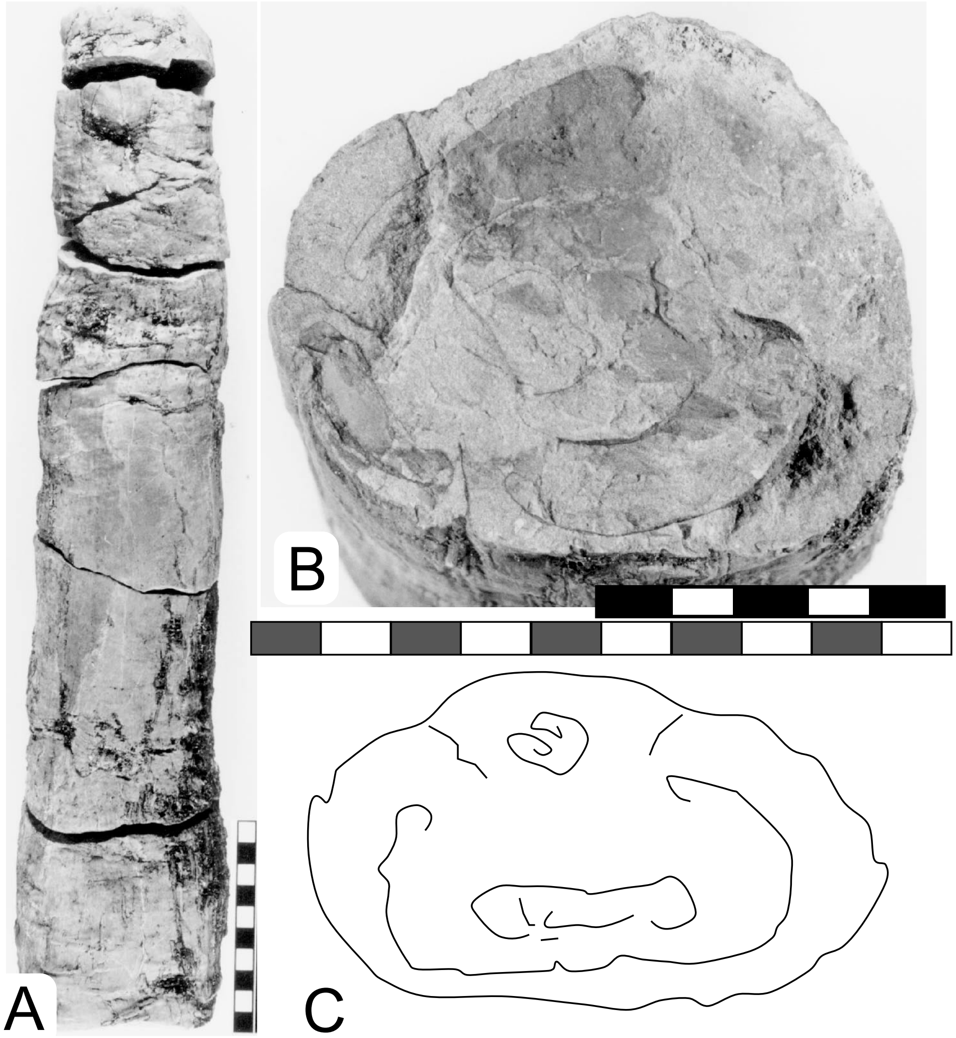


Figure 6. Erect marattialean fern assigned to *Psaronius simplicaulis.* (A) Partial segment of fern axis exhibiting leaf scars and adventitious roots. (B) Cross section of stem in which the vascular architecture (stele) has been preserved in vertical orientation. (C) Line illustration of stem cross section illustrating the vascular architecture of the tree. All scales in centimeters.

indicators (current ripples, oriented macrodetritus, tool marks) record orientations to the southeast to southwest. Time-series analysis of data from the Jagger to Blue Creek interval using the maximum entropy method of power-spectrum analysis reveals strong periodic components that occur at 18 and 200 laminations per cycle (Demko et al., 1991). Trace fossils include horizontal burrows (*Paleophycus*, *Treptichnus*), vertical dwelling (*Rosselia*) and resting (*Lingulichnus*, *Lockiea*) traces, feeding burrows (*Parahaentzschelinia*, *Helminthopsis*), surface trails (e.g., *Kouphichnium*, *Cincosaurus*), and grazing traces (*Haplotichnus*) (Rindsberg, 1990).

In thin section (Figure 3A), the fossiliferous mudstone is recognizable because of the occurrence of bedded, three-dimensionally distributed plant detritus. Plant fossils vary in their disposition relative to bedding and may be found anywhere from horizontal to greater than 45° from horizontal. The majority of preserved organic matter, representative of leaves, is no greater than 0.2 mm (0.008 in.) thick, whereas thicker organic layers, which represent compressed plant axes, attain thicknesses of greater than 3 mm (0.12 in.) and are orientated horizontal to 20° from horizontal. A point count of the sediment clasts indicates that the interval is dominated by quartz and clay, with clasts ranging in size from 0.01 to 0.005 mm

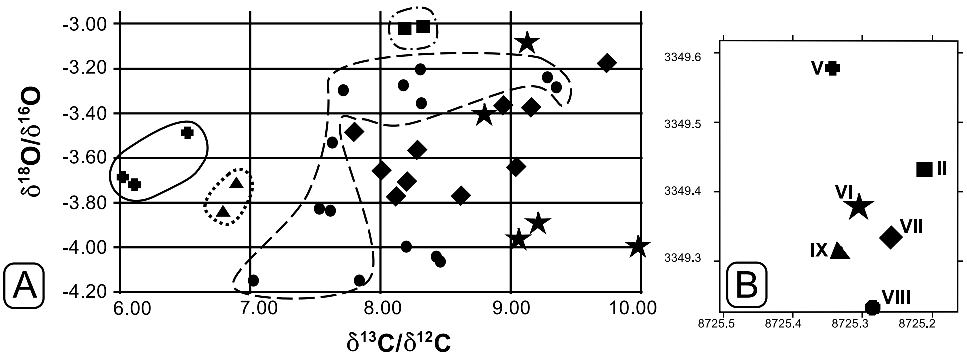


Figure 7. Isotope analyses of siderite carbonate nodules recovered from within and above the preserved Blue Creek forest floor. (A) Plot of $\delta^{13}C/^{12}C$ vs. $\delta\ ^{18}O/^{16}O$ isotope data. (B) Distribution of samples' sites in the Cedrum mine.

(0.0004 to 0.0002 in.) (fine- to very fine-grained silt). The only primary sedimentary structures observable consist of thin, discontinuous parallel laminae, which are identical to the tidalite facies. Laminations are found in and overlying the Blue Creek coal, as well as in the forest-litter hollow voids in degraded plant axes (Figure 3A).

In thin section (Figure 3C), the tidalite facies is recognizable by the presence of uninterrupted lamination of alternating very fine sandstone and siltstone and/or siltstone and mudstone. A near-total absence of organic matter occurs in these rhythmites but where present, consists of either isolated pinnules, axes, or degraded and dispersed organic clasts ranging in size from 0.001 to 0.005 mm (0.00004 to 0.0002 in.). Notably, however, the composition and texture of the sediment is identical to that in the forest-floor litter horizon below, the contact of which is gradational (Figure 3).

Preservation of the Blue Creek Mire

The preserved forest-floor litter and standing forest indicate very rapid sedimentation, with burial of the leaf litter on the order of days to weeks and burial of erect trees probably on the decadenal scale. Based on Holocene studies of plant decay in tropical clastic swamps and mires (Burnham, 1993; Gastaldo and Staub, 1999 and references therein), the pristine preservational state of aerial plant parts in the upper part of the litter horizon indicates that these elements were not exposed to decay processes for any extended period of time. This is in contrast with the debris preserved at the contact between the coal and the roof-shale flora (sensu Gastaldo et al., 1995b).

In Holocene tropical forest litters, decay rates and leaf half-lives are highly variable and dependent on the composition of the leaf (both cellular configuration and biochemistry; table 2 of Gastaldo and Staub, 1999). In humid tropical forests, *k*-values (decay constants) have been reported to range between 1 ($k = 1$ indicates that a leaf will be degraded completely in 1 yr) and 4 (degraded completely in 1.5 months, e.g., Cuevas and Medina, 1988). Although *k*-values of 7.5 have been reported for particular taxa (Bernhard-Reversat, 1972), other reports indicate very low decomposition rates on the order of $k = 0.4–0.5$ (e.g., Irmler and Furch, 1980). These latter rates probably are the result of low nutritional value in the decomposing litter (Edwards, 1977; Klinge, 1978). In alluvial and dipterocarp forests of equatorial southeast Asia, half-lives have been reported to be as little as a few weeks (e.g,. Lavelle et al., 1993) to more than half a year (Anderson et al., 1983).

Leaf-litter fall in the tropics occurs throughout the year (e.g., Burghouts et al., 1992), as leaves become nonfunctional and are lost physiologically. Equatorial forests have been reported to produce total litter fall (including branches) between 9.3 and 10.9 t ha^{-1} yr^{-1}, whereas leaf-litter fall (sensu stricto) has been reported to average 6.7 t ha^{-1} yr^{-1} (Bray and Gorham, 1964). Total fine-litter and leaf-litter productivity in lowland dipterocarp forests of peninsular Malaysia range from 7.5 and 5.4 (Gong and Ong, 1983) to 10.6 and 6.3 t ha^{-1} yr^{-1} (Ogawa, 1978), whereas Proctor et al. (1983) reported values of 8.8 and 5.4 t ha^{-1} yr^{-1} for lowland dipterocarp forests in Sarawak. A pronounced peak in litter fall may occur when either dry (e.g., Gong and Ong, 1983), wet (Ogawa, 1978), or very windy conditions prevail (Proctor et al., 1983). It can be assumed that Carboniferous peat-mire forests produced similar quantities of biomass per year depending on the vegetational mosaic, and that both physiological and traumatic (Gastaldo and Staub, 1999) litter production was responsible for peat accumulation.

The residency time of leaves on tropical forest floors is generally short (on the order of weeks) because of bacterial, fungal, and saprophagous interactions, as well as the adherence of, and degradation by, fine roots of the underlying superficial root mat (Cuevas and Medina, 1988). This combination results in rapid cellular deterioration and destruction of internal anatomy, the interlocking of leaves via fungal growth, and leaf skeletonization (the loss of soft tissues between the "veins;" Gastaldo, 1994). The superficial root mat captures or extracts (via mycorrhizal associations) nutrients from decomposing litter (Stark and Jordan, 1978). The organic residuum is incorporated into the peat matrix.

Tropical forests experience varied leaf-fall patterns and generally do not go through one large pulse of leaves entering the system (Stout, 1980), although leaf flushing may correlate with either the wet or dry season (e.g., Leigh and Windsor, 1996). Because there is no change in tropical temperatures throughout the year that may alter the rate of microbial decay (Stout, 1980), the near-constant addition of canopy parts replenishes the leaf-litter mat, maintaining a relatively constant thickness over time. In addition, as decay rates are also constant because of prevailing climate, degraded organic matter continually is contributed to the peat, accounting for the high accumulation rates as observed in the literature (Anderson, 1983). Therefore, the mechanism(s) responsible for the preservation of unaltered, nondecayed leaves (those without signs of cellular catabolysis, skeletonization, or fungal penetration) in the forest-floor litter of a peat mire must provide for a bypass of the day-to-day degradation processes operating therein. Hence, the "fresh" state of the Blue Creek roof "shale" flora (Gastaldo et al., 1995b), comprising both "delicate" and "robust" taxa (e.g., *Sphenopteris* cf. *schatzlarensis* and *Neuralethopteris schlehani*, respectively), is indicative of an extremely short residence time at the forest-floor surface, probably on the order of several weeks prior to burial and preservation. Based on a physical count of the tidal couplets found in the leaf litter (Figure 3A), a minimum of 1 month must have transpired before the leaf-litter horizon was buried completely.

Continued rapid burial for some extended time is further supported by the presence of the in situ trunks of all major systematic groups, except *Cordaites* (*Artisia* pith casts have been identified in the forest litter, but aerial stems have not been encountered; Stevanoviç-Walls, 2001; Ware, 2001). Erect lycopsid trunks are cast by the same pinstripe lithology found in the entombing tidalite sequence (Gastaldo, 1992). These trees, composed of more bark (periderm) than either wood or soft (parenchyma) tissues, were buried to heights of at least 4.5 m (15 ft) prior to death, resulting in the presence of a second canopy litter horizon at this level (Demko and Gastaldo, 1996) and in decay. Once the structural integrity of the trunk was compromised by rot, the stem and canopy above the level of burial would have fallen over, exposing the hollowed entombed axis. Sediment transported into the system then filled each void (Gastaldo, 1986a, b), resulting in the tree cast (Figure 4). Because of the differential rates of decay for the variety of plant tissues found in a lycopsid trunk (Gastaldo, 1986b), it is not possible to place any constraint on the amount of time from burial to casting.

Similarly, *Calamites* stems are cast by tidalite sedimentation (Figure 5B) (Gastaldo, 1992). However, unlike the lycopsids that were determinate in growth strategy, calamiteans had regenerative capabilities (Gastaldo, 1992). Buds, which would have been capable of developing into aerial leaves and/or branches with leaves at nodes, redifferentiated into rooting structures that grew downward following burial across primary sedimentary structures (Figure 5A). Additionally, new aerial stems grew from buried nodes upward out of the sediment (Gastaldo, 1992) (Figure 2), resulting in another stand of calamiteans at a higher stratigraphic level. These, too, ultimately were preserved by burial and casting in tidalite sediments (Gastaldo, 1992, Figure 6). The central piths of these plants are hollowed by cellular breakdown during growth, and this central void is not the result of tissue decay following plant death. Therefore, it is not possible to place a constraint on timing between burial and casting of these forest constituents.

The most instructive erect elements are the Marattiallean tree ferns. Living marattialeans possess very few thick-walled structural cells (sclerenchymatous tissue) in their stems; instead, the principal structural cell is the main-stem, water-conducting system (cauline vasculature of primary xylem) that "floats" in soft spongy tissue (cortical tissue of undifferentiated parenchyma). These ferns also produce a sheath of secondary (adventituous) roots surrounding the trunk, adding support for these small trees. Such features also are found in Carboniferous representatives (Stewart and Rothwell, 1993). The life habit of these tree ferns is such that the trunk can be essentially dead as much as 1 m (3.3 ft) or so from the apex, and the plant continues to produce photosynthetic leaves. The stem is commonly dead and rotted away near the base of large plants; hence, the inner adventitious roots are contributing to the support of the plant, but probably do not play any additional role. In essence, the entire tree is really a short plant on top of a platform made up of formally living stem and roots (G. Rothwell, 2002, personal communication).

Erect Blue Creek tree ferns retain their vascular architecture (Figure 6B) in the siliciclastic internal cast. This feature indicates that following burial, sufficient time passed for the soft, fleshy parenchyma tissues of the upper "living" tree to have decayed, but the more resistant conducting cells remained essentially erect prior to sediment infill. Parenchymal tissue decay correlates generally with a decay half-life (Gastaldo and Staub, 1999), which can be as short as a few weeks in the wet tropics. Hence, these standing tree ferns allow for a constraint on how quickly internal decay of erect vegetation occurred following (or coincident with) burial and the timing of subsequent infill, which would have been on the order of a few months.

Demko (1990b) evaluated a continuous 5-m (16-ft) drill core of tidalite sediments recovered from between the Jagger and Blue Creek coals at the Hope Galloway mine, Walker County, Alabama. Ninety neap-spring-neap tidal cycles were identified in the first 1340 sandstone laminae (1.75 m [6 ft] in thickness), from which a semidiurnal system in some neap-spring-neap cycles and diurnal tides recorded during other cycles was interpreted (Demko et al., 1991). Present neap-spring-neap tidal cycles are 14.77 days, with Carboniferous neap-spring-neap cycles estimated to have been 15 days (A. Archer, 2002, personal communication). Using this estimate, it would have taken approximately 20 yr to bury the tallest lycopsid encountered (not considering the decompacted mud portion of each cycle; if the mudstone is decompacted, burial may have been on the order of a decade). Therefore, the sedimentation event responsible for burial of the forest-floor litter, removing it from decay processes operating at the surface of the peat mire, and the entombment of the standing forest, which thereafter underwent decay and casting, can be constrained to the order of a decade or less.

DISCUSSION

The burial of the peat forest by tidal sedimentation was the result of a rapid transgression that generated sufficient accommodation space to preserve standing trees to at least a height of 4.5 m (15 ft). In addition, accommodation was generated to overcome the thickness of the Blue Creek peat body, interpreted as a planar, immature, raised mire (Demko and Gastaldo, 1992). Decompaction of the Blue Creek coal based on the relative plant-part composition of the peat (Winston, 1990a) results in an original peat-body thickness ranging between 3 and 6 m (10 and 20 ft) over an outcrop area of at least 1100 km^2 (425 mi^2) (Demko and Gastaldo, 1992). The paleogeographic position of the Cedrum mine has been placed some 60–100 km (37–62 mi) from the shoreline at the time of Blue Creek mire accumulation (J. Pashin, 2002, personal communication). Hence, when the thickness of the peat body in Walker County is added to the documented maximum lycopsid-trunk height, a minimum of 11 m (36 ft) of accommodation is required for preservation of this assemblage.

Demko and Gastaldo (1996) concluded that eustasy was the dominant allocyclic mechanism responsible for the emplacement of fully marine sediments above ravinement indicators (Liu and Gastaldo, 1992b). Conversely, the emplacement of tidal facies between peat mires was ascribed to autocyclic mechanisms as the result of peat compaction following catastrophic flooding of the mire (Gastaldo, 1990) and burial of the forest (Demko and Gastaldo, 1996). Based on the present analyses, this model requires reinterpretation, and allocyclic processes are implicated.

Accommodation space can be generated by either eustatic rise or tectonic subsidence, the magnitude of which still is debated (e.g., Klein, 1994) and probably cannot be generalized in cyclothems. This is because the mechanism is dependent on basinal history (Klein and Willard, 1989) and regional variation in tectonically active areas (Fortuin and de Smet, 1991). What must be taken into consideration in the Black Warrior Basin is not only the rapidity at which the Blue Creek peat mire was placed below base level but also the depth below base level that allowed for preservation of the forest under an estuarine meso- to macrotidal system, the regime in which tidal rhythmite deposits are generated (Tessier et al., 1995). Given the constraints of tropical plant decay, the final series of events responsible for base-level change occurred on the order of decades and possibly less.

Recent papers (e.g., Clark et al., 2002; Blanchon et al., 2002) indicate that eustatic rise during the present interstadial has been pulsed, with rapid deepening occurring globally. The global meltwater pulse IA (MWP-IA) at the beginning of the last deglaciation about 14 ka is recorded in corals in Barbados (Bard et al., 1990) and elsewhere, resulting in an average rise of 20 m (66 ft) in less than 1000 yr (Clark et al., 2002). However, because of the proximity of any geographical site to melting of the ice cap, actual sea level rise might be as little as about 75% or as much as about 142% of the eustatic mean. With meltwater contribution from Antarctica and data from Barbados and the Sunda Shelf, Clark et al. (2002) demonstrated an approximate 25-m (82-ft) rise in eustatic sea level in the tropics over a period of only 700 yr. If this rise was continuous, the rate would exceed 40 mm/yr (1.6 in./yr) (Clark et al., 2002). Other meltwater pulses have been identified in the Holocene record and interpreted on similar timescales.

Blanchon et al. (2002) have interpreted relic reefs on Grand Cayman, Barbados, St. Croix, St. Thomas, and northern Florida to have stopped accreting within 160 yr of each other, whereas modern reefs became established at depths 4–9 m (13–30 ft) higher upslope within 100 yr of the former's demise (if the older radiocarbon dates, uncorrected for metabolic fractionation, are accurate). The change in elevation of reef growth is explained by a rapid rise in sea level of at least 6 m (20 ft); hence, evidence exists for a circum-Caribbean backstepping response on a century scale, with the rate of sea level rise on the order of 60 mm/yr (2.4 in./yr). The modal age of Holocene deltas around the globe also record initiation over a 400-yr-interval, backstepping upslope (Stanley and Warne, 1994) that coincides with the reef demise.

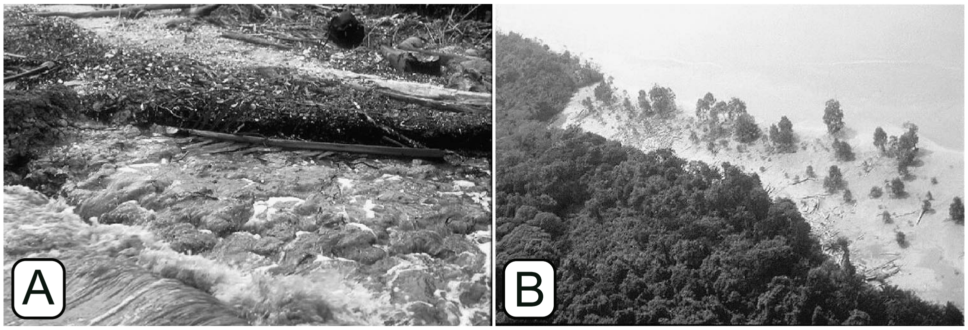


Figure 8. Features of Holocene coastal-plain and deltaic transgression under eustatic control in Kalimantan, Indonesia, and Sarawak, east Malaysia. (A) Transgression of coastal-plain deposits south of the Tandjung Tambangotngot, Mahakam River delta. Wave action has eroded organic-rich sediments from above a rooted inceptisol and deposited shell- and organic-rich beach sediments. Photo taken October 1988. (B) Oblique aerial photograph of coastal mangrove transgression in the Rajang River delta, showing undercutting of rooting systems, felling of vegetation, and transport of woody debris into the South China Sea. Photo taken by K. Bartram, July–August 1993.

An eustatic rise in sea level, similar to documented backstepping, cannot account for the rapid generation of accommodation necessary for Blue Creek forest preservation even if the peat-mire surface, some 60–100 km (37–62 mi) inland, was within 1 m (3.3 ft) or so of base level (hence, reducing required accommodation to $\sim$5 m ($\sim$16 ft); see below). Water level would have had to rise at a rate between 500 and 1000 mm/yr (0.5–1.0 m/yr [1.6–3.3 ft/yr]) to generate accommodation, allowing for initiation of sedimentation, burial of standing trees by diurnal tidal deposits, and subsequent decay and infill of the axial voids. Holocene rates are an order of magnitude lower than that required to bury and preserve the forest, and where coastal transgression presently is occurring in the tropics, trees either are being felled and transported oceanward or are covered with a thin veneer of beach sediment (Figure 8). If eustatic rise occurred at documented Holocene rates, the lycopsid aerial canopy parts shed after death would be preserved in close proximity to the forest-floor litter. Instead, these assemblages are preserved along with mud-cast prostrate trees at the stratigraphic level, where the standing trees terminate (Figure 4). Hence, eustatic sea level rise alone would have been too slow to generate water depths to account for both the observed sedimentological sequence and the plant taphonomic character of the assemblage.

The alternative allocyclic mechanism to account for the requisite accommodation is tectonism. Phillips et al. (1994) and Phillips and Bustin (1996) reported the transgression of a Holocene coastal mangrove peat as the result of earthquake-induced subsidence in a Panamanian microtidal system. The back-barrier Changuinola peat deposit (Cohen et al., 1989) covers approximately 60 km^2 (23 mi^2) onshore and another 20 km^2 (8 mi^2) offshore beneath shallow-marine sediments of Almirante Bay. The ^{14}C AMS age of the peat, −8.10 m (−26.5 ft) beneath the present mire surface, is reported as 3.04 ± 0.08 ka, with nearly 40% of the peat body presently beneath sea level (Phillips and Bustin, 1996). Cohen et al. (1985) report an approximate age of the basal peat body as between 4 and 5 ka, and Phillips and Bustin (1996) concur; their basalmost age determination is approximately 2 m (6.6 ft) above the contact with underlying sand. An earthquake of $M_{\mathrm{s}} = 7.5$ on April 22, 1991, led to a minimum of 30 cm (12 in.) and a maximum of 50–70 cm (20–28 in.) of coseismic subsidence and flooding or drowning of the southeastern margin of the mire. Phillips and Bustin (1996) concluded that the rate of tectonically driven, punctuated subsidence in the area is between 2.2 and 2.6 mm/yr (2.2–2.6 m/k.y.), and the disposition of marginal peat records this style of subsidence for at least the past 2 k.y. and probably longer.

Earthquake-induced subsidence of 1 m (3.3 ft) or more per event is documented along the Chilean (Plakker and Savage, 1970), northwestern United States (Atwater and Yamaguchi, 1991), and Alaskan (Plafker and Rubin, 1967; Plafker, 1969) coasts. Central Chile was devastated by an $M_{\mathrm{s}} = 7.5$ (May 21, 1960) earthquake followed by two closely spaced $M_{\mathrm{s}} = 8.5$ (May 22, 1960) earthquakes during which time both coseismic uplift and subsidence relative to sea level occurred along the coast over an area of 200,000 km^2 (77,220 mi^2). Vertical displacements were determined by differences in the height of pre- and postquake positions of the lower vegetational growth limit. Plafker and Savage (1970) reported that subsidence occurred in an area that was 75–100 km (47–62 mi) wide and at least 800 km (497 mi) in length. Local maximum coseismic subsidence was as much as −2.7 m (−8.8 ft) on unconsolidated sediments near Valdivia, with this area experiencing an average subsidence of −1.8 m (6 ft). Adjacent coastal farmland was submerged permanently by at least 2 m (7 ft), whereas submergence at bedrock sites on Isla Chiloé was as much as 2.4 m (8 ft). Similar coseismic displacements (1 m [3.3 ft] average, 2.2 m [7.2 ft] maximum subsidence) followed the 1964 Alaskan Earthquake (Plafker, 1965; Plafker and Rubin, 1967), and submerged forests along the coast of Washington state are indicative of at least 1-m (3.3-ft) subsidence (Atwater and Yamaguchi, 1991). In some Chilean coastal areas, post-earthquake subsidence of a few decimeters continued for several years.

Historical records provide data on earthquake frequency along the Chilean coast (Lomnitz in Plafker and Savage, 1970). Earthquakes in the Valdivia region with estimated $M_s > 7.5$ occurred in 1575, 1737, and 1837; major earthquakes centered on Concepción occurred in 1570, 1575, 1751, and 1835; and Arauco Indian folklore notes at least two large earthquakes were accompanied by submergence in the Lake Budi area, north of Valdivia. Hence, the recurrence interval for high-magnitude earthquakes along this part of the Chilean coast is somewhat less than 100 yr since the early part of the 16th century. If the average coseismic subsidence associated with each of these high-magnitude events is a conservative 1.5 m (5 ft), then 6–7.5 m (20–25 ft) of cumulative subsidence could have occurred in less than 450 yr. Hence, if the cumulative effect of such short-term subsidence events can lower the base of a peat body while the mire is accumulating organic material, without concurrent siliciclastic contamination (Phillips and Bustin, 1996), then siliciclastic sediments will be deposited only when the peat-mire forest floor finally is submerged below sea level.

Therefore, coseismic, tectonically induced subsidence associated with high magnitude activity is the most parsimonious explanation to account for the preservation of the Blue Creek mire. This model involves transgression of the coastal zone by backstepping generated by century- to millennial-scale coseismic events, placing the top of the mire close to base level. The actual coastline would have been kilometers distant of the Cedrum mine, where coeval tidal sediments would have been deposited. Although marine or estuarine waters would have been in close proximity to the study site, peat continued to accumulate under freshwater conditions because of the hydraulic head inherent in planar and raised mires (Winston, 1994). Subsequently, an anomalous high-magnitude earthquake (or series of closely spaced earthquakes) resulted in the displacement of the forest floor to at least 5 m (16 ft) below sea level (accommodation required to account for the maximum lycopsid height). Such vertical displacement would have affected fluvial distribution patterns in the area and, possibly, increased sediment loading from slope failure in the hinterland. Such sediment loading may account for the rapid deposition of very fine sand and coarse silt in tidal rhythmites found within and above the mire, with redistribution of sediment-water interface clastics into the vertical voids produced when entombed trees decayed. Sediment transported and deposited occurred in a freshwater regime, as indicated by isotopic data from siderite concretions. The presence of tidal deposits in the upper reaches of estuaries and in fluvial-dominated systems is common where meso- to macrotidal ranges occur (e.g., Mahakam delta, Gastaldo et al., 1995a; Rajang delta, Staub et al., 2000; Fly River Delta, Baker et al., 1995).

Confirmation of Tectonic Influence on Black Warrior Sedimentation

Tectonic influence on sediment accumulation in the greater Black Warrior Basin first was suggested by Thomas (1968), and Weisenfluh and Ferm (1984) recognized this phenomenon as affecting peat distribution during accumulation of the Pratt coal seam. They recognized basement faulting contemporaneous with peat accumulation as evidenced by the presence of increasing sediment thicknesses on fault blocks from the edge of the basin successively southward. Such contemporaneous faulting influenced the peat distribution across the basin, with thick merged coals occurring on the upthrown sides of fault blocks and thin coal splits on the downthrown sides (Weisenfluh and Ferm, 1984, Figure 4). They tested this hypothesis using data recovered from 200 core logs and underground seam measurements in a small geographic area. Although never stated directly as to whether the observed displacement was restricted only to contemporaneous faulting, lithologies that intervene between coal splits on the downthrown side of the fault block may be 45–60 m (148–197 ft) in thickness. This would imply that localized subsidence, contemporaneous with peat accumulation, could account for the rapid change in base level, drowning, and preservation of forests in this basin. Penecontemporaneous faulting associated with the development of the Mary Lee cycle has been documented by Pashin (1994c).

Implications for Subsidence Rates

In an analysis of Cenozoic tectonism in the Banda Sea, Indonesia, Fortuin and de Smet (1991, Figure 5) calculated the average subsidence and uplift rates since the Miocene, but cautioned that the actual subsidence rates may be higher because neither compaction nor isostasy caused by sediment loading were considered for the sake of simplicity. It is evident from their data that the timing, rates, and magnitudes of vertical crustal movement vary from place to place across the Banda Sea. For example, average subsidence rates at Buru (early to middle Miocene) are 30 cm/ka (12 in./ka), Buton (middle–late Miocene) experienced rates of greater than 75 cm/ka (30 in./ka), whereas Seram (late Miocene–late Pliocene) experienced a rate slightly less than 75 cm/ka (30 in./ka). They argued, however, that local subsidence is episodic near convergent margins over very short temporal scales and concluded that processes operating over several orders of magnitude of time result in an intricate pattern of both uplift and subsidence. Pashin (2004) has modeled subsidence rates for the Mary Lee cycle ranging from a minimum of 12 cm/ka (5 in./ka) to a maximum of 45 cm/ka (18 in./ka), with increasing rates higher in the Pottsville Formation. These figures fall in the lower range of values calculated by Fortuin and de Smet (1991) and are slightly more than half of the fastest subsidence rate. Composite sections used in Pashin's (2004) analysis originated from either Lamar or Tuscaloosa Counties, approximately 65 and 100 km (40 and 62 mi) southwest and south of the Cedrum mine, respectively. At the Cedrum mine, the Jagger, Blue Creek, and Mary Lee coals are in closer stratigraphic proximity to each other.

Pleistocene sediments in the Rajang River delta consist of beach/terrace deposits, some 5–7 m (16–23 ft) higher than mean sea level (MSL), adjacent to upland areas which Staub and Gastaldo (2003) interpret as the remains of the VIIa highstand surface of 125 ka, some 6 m (20 ft) above present MSL (Chappell and Shackleton, 1986). In the lower delta plain, near Daro, subsurface peat recovered from a depth of 78 m (256 ft) below MSL has a ^{14}C age date of 40,370 (+2944/−2150; Staub and Gastaldo, 2003). This peat is part of the IIIb highstand of 40 ka, which occurred at 41 ± 4 m (135 ± 13 ft) below present MSL (Bloom et al., 1974; Chappell and Shackleton, 1986). These relationships imply that approximately 40 m (131 ft) of subsidence has occurred since then, averaging nearly 1 m/ka (3.3 ft/ka). Hence, it is not impossible to envision a major tectonic event, such as the Alaskan (Plafker, 1969) or Chilean (Plafker and Savage, 1970) earthquake, wherein the extent of basinal subsidence would have been equal to the cumulative average displacement for 10 ka or more.

Calculated average subsidence rates impart an assumption that base-level changes are gradual and extended over temporal durations of millennial scale. Such paradigms are not substantiated fully by processes operating in tectonically active areas, and there is reason to believe that coseismic changes in base level have had their effect on the stratigraphic record of various basinal configurations. Although average subsidence rates provide a means by which to evaluate overall long-term basinal history, the recognition and identification of in situ erect forests preserved in estuarine deposits are a key in understanding not only the pulsed nature of basinal response, but also provide a means to evaluate the magnitude of coseismic subsidence in the deep past. The height to which these forests are preserved serves as a proxy for localized, tectonically rapid subsidence.

CONCLUSIONS

The low-ash, low-sulfur (Winston, 1990b) Blue Creek mire was deposited at the inflection point of the sea level curve recorded in the Mary Lee cycle (Gastaldo et al., 1993). Eustasy alone cannot explain tidalite deposition within and above the Blue Creek mire. Documented Holocene rates of sea level rise (Bard et al., 1990; Blanchon et al., 2002; Clark et al., 2002) when applied to the Carboniferous are too slow to account for the burial and preservation of the in situ lycopsids, calamiteans, and particularly, the tree ferns. Such a mechanism could account for buried forests in which tree trunks are less than 1 m (3.3 ft) in height (e.g., Gastaldo, 1986a), but not for trees preserved to heights of several meters. Given the fact that progressive burial of the margins of a peat body can occur during backstepping (either eustatic or tectonic) without affecting the mire's sulfur and clastic content (the overlying clastics are either a roof shale or coal parting depending on subsequent events; Gastaldo et al., 1995b; Phillips and Bustin, 1996), it is possible that some part of the westward and northwestward extension of the Blue Creek mire may have been submarine, effectively bringing the top of the peat closer to base level, prior to the time when the standing forest was preserved in Walker County. Hence, it is not necessary to invoke a single, short-term event to account for 11 m (36 ft) of subsidence to bury the peat body and the forest; instead, total subsidence would be less than this requisite base-level change, but would still be on the order of 5 m (16 ft) to account for burial of the tallest in situ trees.

Rapid, coseismic subsidence, however, can significantly change base level on local (e.g., Weisenfluh and Ferm, 1984; Staub and Gastaldo, 2003) or regional scales (Plafker, 1965; Plafker and Savage, 1970; Fortuin and de Smet, 1991). Although average long-term subsidence rates are relied on to characterize basinal history, neotectonic investigations have demonstrated that long-term uplift and subsidence rates tend to be considerably lower than those calculated for shorter durations (e.g., Tjia, 1981; Bloom and Yonekura, 1985). Depending on the magnitude of any single tectonic event, subsidence may be less than 1 m (3.3 ft) (e.g., Phillips and Bustin, 1996) or as much as 4 m (13 ft) (Prince William Sound, Alaska; Plafker, 1969) of vertical displacement. Evidence exists in the Mary Lee cycle for tremor-induced liquifaction of sand bodies (Demko, 1990a, b), indicating that effects of tectonic loading associated with the Appalachians and Ouachitas (Thomas, 1988, 1995) are recorded in this sedimentological record. Therefore, it is most parsimonious that earthquake-induced subsidence was responsible for the documented dramatic change in the elevation of the Blue Creek mire, reducing it to several meters below base level, and allowing for tidal processes operating in a freshwater regime to bury and preserve this forest. The model proposed by Gastaldo (1990) and discussed by Demko and Gastaldo (1996) for the burial and preservation of the Blue Creek forest via catastrophic high-magnitude fluvial processes for leaf-litter burial and preservation is untenable. Although autocyclic compaction (Demko and Gastaldo, 1996) may have played some role in positional change of base level, allocyclic coseismic processes are implicated as the primary mechanism for overriding and preserving the Blue Creek peat mire.

The recognition that sedimentation following coseismic subsidence is the mechanism responsible for entombment and burial of in situ erect forests above coastal-plain mires allows for the use of such terrestrial plant-fossil assemblages as a proxy for understanding the magnitude of episodic base-level change in the stratigraphic record. Hence, short-term tectonic subsidence events can be identified in terrestrial/transitional regimes by close examination of the sedimentological features associated with in situ forests, irregardless of geologic age, and using such evidence, a better understanding of the short-term spasmodic changes in base level that are time averaged into long-term subsidence rates can be ascertained.

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REFERENCES CITED

Anderson, J. A. R., 1983, The tropical swamps of western Malaysia, *in* A. P. J. Gore, ed., Mires, swamp bog, fen, and moor. Ecosystems of the world, regional studies 4B: Amsterdam, Elsevier, p. 181–200.

Anderson, J. M., J. Proctor, and H. W. Vallack, 1983, Ecological studies in four contrasting lowland rainforest in Gunung Mulu National Park, Sarawak: 3. Decomposition processes and nutrient losses from leaf litter: Journal of Ecology, v. 71, p. 503–527.

Atwater, B. F., and D. K. Yamaguchi, 1991, Sudden, probably coseismic submergence of Holocene trees and grass in coastal Washington state: Geology, v. 19, p. 706–709.

Baker, E. K., P. T. Harris, J. B. Keene, and S. A. Short, 1995, Patterns of sedimentation in the macrotidal Fly River delta, Papua New Guinea, *in* B. W. Flemming and A. Bartholomä, eds., Tidal signatures in modern and ancient sediments: International Association of Sedimentologists Special Publication 24, p. 193–211.

Bard, E., B. Hamelin, R. G. Fairbanks, and A. Zindler, 1990, Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals: Nature, v. 345, p. 405–409.

Barnett, R. L., 1986, Coal occurrence and general geology in the Townley 7.5-minute quadrangle, Walker County, Alabama: Alabama Geological Survey Special Map 166, 79 p.

Bernhard-Reversat, F., 1972, Décomposition de la litiPre de feuilles en forLt ombrophile de basse Côte-d'Ivoire: Oecologia Plantarum, v. 7, p. 279–300.

Blanchon, P., B. Jones, and D. C. Ford, 2002, Discovery of a submerged relic reef and shoreline off Grand Cayman further support for an early Holocene jump in sea level: Sedimentary Geology, v. 147, p. 253–270.

Bloom, A. L., and N. Yonekura, 1985, Coastal terraces generated by sea-level change and tectonic uplift, *in* R. J. N. Devoy, ed., Models in geomorphology: Winchester, Massachusetts, Allen & Unwin, p. 139–154.

Bloom, A. L., S. W. Broeker, J. M. A. Chappell, R. K. Matthews, and K. J. Mesolella, 1974, Quaternary sea level fluctuations in a tectonic coast, New ^{230}Th/^{234}U from the Huon Peninsula, New Guinea: Quaternary Research, v. 4, p. 185–205.

Bray, J. R., and E. Gorham, 1964, Litter production in forests of the world, *in* J. B. Cragg, ed., Advances in ecological research: New York, Academic Press, v. 2, p. 101–157.

Burghouts, T., G. Ernsting, G. Korthals, and T. Devries, 1992, Litterfall, leaf litter decomposition and litter invertebrates in primary and selectively logged dipterocarp forest in Sabah, Malaysia: Philosophical Transactions of the Royal Society of London, B, v. 335, p. 407–416.

Burnham, R. J., 1993, Reconstructing richness in the plant fossil record: Palaios, v. 8, p. 376–384.

Cecil, C. B., 1990, Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks: Geology, v. 18, p. 533–536.

Chappell, J., and N. J. Shackleton, 1986, Oxygen isotopes and sea level: Nature, v. 324, p. 137–140.

Clark, P. U., J. X. Mitovica, G. A. Milne, and M. E. Tamislea, 2002, Sea-level fingerprinting as a direct test for the source of global meltwater pulse IA: Science, v. 295, p. 2438–2441.

Cohen, A. D., R. Raymond Jr., S. Mora, A. Alverado, and L. Malavassi, 1985, Economic characterization of the peat deposits of Costa Rica, preliminary study, *in* B. Wade, ed., Tropical peat resources—Prospects and potential: International Peat Society, p. 146–169.

Cohen, A. D., R. Raymond Jr., A. Ramirez, Z. Morales, and F. Ponce, 1989, The Changuinola peat deposit of northwest Panama, a tropical, back-barrier peat (coal) forming environment: International Journal of Coal Geology, v. 12, p. 157–192.

Cuevas, E., and E. Medina, 1988, Nutrient dynamics within Amazonian forests: II. Fine root growth, nutrient availability and leaf litter decomposition: Oecologia, v. 76, p. 263–273.

Demko, T. M., 1990a, Depositional environments of the lower Mary Lee coal zone, lower Pennsylvanian "Pottsville" Formation, northwestern Alabama, *in* R. A. Gastaldo, T. M. Demko, and Y. Liu, eds., Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Geological Society of America, Southeastern Section, Field Trip Guidebook, p. 5–20.

Demko, T. M., 1990b, Paleogeography and depositional environments of the lower Mary Lee coal zone, Pottsville Formation, Warrior Basin, northwestern Alabama: M.S. thesis, Auburn University, Auburn, Alabama, 195 p.

Demko, T. M., and R. A. Gastaldo, 1992, Paludal environments of the Mary Lee coal zone, Pottsville Formation, Alabama, stacked clastic swamps and peat mires: International Journal of Coal Geology, v. 20, p. 23–47.

Demko, T. M., and R. A. Gastaldo, 1996, Eustatic and autocyclic influences on deposition of the lower Pennsylvanian Mary Lee coal zone, Warrior Basin, Alabama: International Journal of Coal Geology, v. 31, p. 3–19.

Demko, T. M., J. Jirikowic, and R. A. Gastaldo, 1991, Tidal cyclicity in the Pottsville Formation, Warrior Basin, Alabama: Sedimentology and time-series analysis of an interlaminated sandstone-mudstone interval: Geological Society of America Abstracts with Program, v. 23, p. 287.

Dewey, J. F., and W. C. Pitman III, 1998, Sea-level changes, mechanisms, magnitudes and rates, *in* J. L. Pindell and C. L. Drake, eds., Paleogeographic evolution and nonglacial eustacy, northern South America: SEPM Special Publication 58, p. 1–16.

Dickinson, W. R., G. S. Soreghan, and K. A. Giles, 1994, Glacio-eustatic origin of Permo-Carboniferous stratigraphic cycles; evidence from the southern Cordilleran foreland region: SEPM Concepts in Sedimentology and Paleontology, v. 4, p. 25–34.

DiMichele, W. A., and T. L. Phillips, 1977, Monocyclic *Psaronius* from the lower Pennsylvanian of the Illinois Basin: Canadian Journal of Botany, v. 55, p. 2514–2524.

Edwards, P. J., 1977, Studies of mineral cycling in a montane rain forest in New Guinea: Journal of Ecology, v. 65, p. 971–992.

Fortuin, A. R., and M. E. M. de Smet, 1991, Rates and magnitudes of late Cenozoic vertical movement in the Indonesian Banda Arc and the distinction of eustatic effects: International Association of Sedimentologists Special Publication 12, p. 79–89.

Galloway, W. E., 1989, Genetic stratigraphic sequences in basin analysis: I. Architecture and genesis of flooding-surface bounded depositional units: AAPG Bulletin, v. 73, p. 125–142.

Gastaldo, R. A., 1986a, Implications on the paleoecology of autochthonous lycopods in clastic sedimentary environments of the early Pennsylvanian of Alabama: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 53, 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., 1990, Early Pennsylvanian swamp forests in the Mary Lee coal zone, Warrior Basin, Alabama, *in* R. A. Gastaldo, T. M. Demko, and Y. Liu, eds., Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Geological Society of America, Southeastern Section, Field Trip Guidebook, p. 41–54.

Gastaldo, R. A., 1992, Regenerative growth in fossil horsetails following burial by alluvium: Historical Biology, v. 6, p. 203–220.

Gastaldo, R. A., 1994, The genesis and sedimentation of phytoclasts with examples from coastal environments, *in* A. Traverse, ed., Sedimentation of organic particles: Cambridge, United Kingdom, Cambridge University Press, p. 103–127.

Gastaldo, R. A., and J. R. Staub, 1999, A mechanism to explain the preservation of leaf litters lenses in coals derived from raised mires: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 149, p. 1–14.

Gastaldo, R. A., T. M. Demko, Y. Liu, W. D. Keefer, and S. L. Abston, 1989, Biostratinomic processes for the development of mud-cast logs in Carboniferous and Holocene swamps: Palaios, v. 4, p. 356–365.

Gastaldo, R. A., T. M. Demko, and Y. Liu, 1990, Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: A Guidebook for Field Trip VI, 39th Annual Meeting Southeastern Section of the Geological Society of America, Tuscaloosa, Alabama. Geological Survey of Alabama, 139 p.

Gastaldo, R. A., T. M. Demko, and Y. Liu, 1991, A mechanism to explain persistent alternation of clastic and peat-accumulating swamps in carboniferous sequences: Bulletin Societé Geologié France, v. 8, p. 155–161.

Gastaldo, R. A., T. M. Demko, and Y. Liu, 1993, Application of sequence and genetic stratigraphy concepts to Carboniferous coal-bearing strata, an example from the Black Warrior Basin, U.S.A.: Geologische Rundschau, v. 82, p. 212–226.

Gastaldo, R. A., G. P. Allen, and A. Y. Huc, 1995a, The tidal character of fluvial sediments of the Recent Mahakam River delta, Kalimantan, Indonesia, *in* B. W. Flemming, and A. Bartholomä, eds., Tidal signatures in modern and ancient sediments: International Association of Sedimentologists Special Publication 24, p. 171–181.

Gastaldo, R. A., H. W. Pfefferkorn, and W. A. DiMichele, 1995b, Taphonomic and sedimentologic characterization of roof-shale floras, *in* P. C. Lyons, E. D. Morey, and R. H. Wagner, eds., Historical perspective of early twentieth century Carboniferous paleobotany in North America: Geological Society of America Memoir 185, p. 341–351.

Gautier, D. L., 1982, Siderite concretions: Indicators of early diagenesis in ancient sediments by analogy with processes in modern diagenetic environments, *in* D. A. McDonald and R. C. Surdam, eds., Clastic diagenesis: AAPG Memoir 37, p. 111–123.

Gong, W. K., and J. E. Ong, 1983, Litter production and decomposition in a coastal hill dipterocarp forest, *in* S. L. Sutton, T. C. Whitmore, and A. C. Chadwick, eds., Tropical rain forest, ecology and management: Oxford, United Kingdom, Blackwell Scientific Publications, p. 275–285.

Irmler, U., and K. Furch, 1980, Weight, energy and nutrient changes during decomposition of leaves in the emersion phase of Central Amazonian inundation forests: Pedobiologia, v. 20, p. 118–130.

Klein, G. D., 1994, Depth determination and quantitative distinction of the influence of tectonic subsidence and climate on changing sea level during deposition of mid-continent Pennsylvanian cyclothems: SEPM Concepts in Sedimentology and Paleontology, v. 4, p. 35–50.

Klein, G. D., and D. A. Willard, 1989, Origin of Pennsylvanian coal-bearing cyclothems of North America: Geology, v. 17, p. 152–155.

Klein, G. D., and J. B. Kupperman, 1992, Pennsylvanian cyclothems: Methods of distinguishing tectonically induced changes in sea level from climatically induced changes: Geological Society of America Bulletin, v. 106, p. 166–175.

Klinge, H., 1978, Litter production in tropical ecosystems: Malayan Nature Journal, v. 30, p. 415–422.

Kosanke, R. M., 1979, A long-leaved specimen of Lepidodendron: Geological Society of America Bulletin, v. 90, p. 431–434.

Krasilov, V. A., 1975, Paleoecology of terrestrial plants, Basic principles and techniques: New York, Wiley Publishing, 283 p.

Lavelle P., E. Blanchart, A. Martin, and S. Martin, 1993, A hierarchical model for decomposition in terrestrial ecosystems, applications to soils of humid tropics: Biotropica, v. 25, p. 130–150.

Leigh, E. G. Jr., and D. M. Windsor, 1996, Forest production and regulation of primary consumers in Barro Colorado Island, *in* E. G. Leigh Jr., A. S. Rand, and D. M. Windsor, eds., The ecology of a tropical forest, seasonal rhythms and long-term changes, 2d ed.: Washington, D.C., Smithsonian Institution, p. 111–122.

Liu, Y., 1990, Depositional environments of the Mary Lee coal zone, lower Pennsylvanian Pottsville Formation, northwestern Alabama, *in* R. A. Gastaldo, T. M. Demko, and Y. Liu, eds., Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Geological Society of America, Southeastern Section, Field Trip Guidebook, p. 21–40.

Liu, Y., and R. A. Gastaldo, 1992a, Characteristics of a Pennsylvanian ravinement surface: Sedimentary Geology, v. 77, p. 197–213.

Liu, Y., and R. A. Gastaldo, 1992b, Characteristics and provenance of log-transported gravels in a Carboniferous channel deposit: Journal of Sedimentary Petrology, v. 62, p. 1072–1083.

Moore, S. E., R. E. Ferrell, and P. Aharon, 1992, Diagenetic siderite and other ferroan carbonates in a modern subsiding marsh sequence: Journal of Sedimentary Petrology, v. 62, p. 357–366.

Mozley, P. S., and P. Wersin, 1992, Isotopic composition of siderite as an indicator of depositional environment: Geology, v. 20, p. 817–820.

Ogawa, H., 1978, Litter production and carbon cycling in Pasoh Forest, Malaysia: Malayan Nature Journal, v. 30, p. 367–373.

Pashin, J. C., 1994a, Flexurally influenced eustatic cycles in the Pottsville Formation (lower Pennsylvanian), Black

Warrior Basin, Alabama, tectonic and eustatic controls on sedimentary cycles, *in* J. M. Dennison and F. R. Ettensohn, eds., SEPM Concepts in Sedimentary and Paleontology, v. 4, p. 89–105.

Pashin, J. C., 1994b, Cycles and stacking patterns in Carboniferous rocks of the Black Warrior foreland basin: Gulf Coast Association of Geological Societies Transactions, v. 44, p. 555–563.

Pashin, J. C., 1994c, Coal-body geometry and synsedimentary detachment folding in Oak Grove coalbed-methane field, Black Warrior Basin, Alabama: AAPG Bulletin, v. 78, p. 960–980.

Pashin, J. C., 2004, Cyclothems of the Black Warrior Basin, Alabama, U.S.A.: Eustatic snapshots of foreland basin tectonism, *in* J. C. Pashin and R. A. Gastaldo, eds., Sequence stratigraphy, paleoclimate, and tectonics of coal-bearing strata: AAPG Studies in Geology 51, p. 199–218.

Pfefferkorn, W. H., 1976, Pennsylvanian tree fern compressions *Caulopteris*, *Megaphyton*, and *Artistophyton* gen. nov. in Illinois: Illinois State Geological Survey Circular 492, p. 1–31.

Phillips, S., and R. M. Bustin, 1996, Sedimentology of the Changuinola peat deposit; organic and clastic sedimentary response to punctuated coastal subsidence: Geological Society of America Bulletin, v. 108, p. 794–814.

Phillips, S., R. M. Bustin, and L. E. Lowe, 1994, Earthquake-induced flooding of a tropical coastal peat swamp: A modern analogue for high-sulfur coals?: Geology, v. 22, p. 929–932.

Plafker, G., 1965, Tectonic deformation associated with the 1964 Alaska earthquake: Science, v. 148, p. 1675–1678.

Plafker, G., 1969, Tectonics of the March 27, 1964, Alaska Earthquake: U.S. Geological Survey Professional Paper 543-I, p. I1–I74.

Plafker, G., and M. Rubin, 1967, Vertical tectonic displacements in south-central Alaska during and prior to the great 1964 earthquake: Journal of Geoscience, Osaka City University, v. 10, p. 53–66.

Plafker, G., and J. C. Savage, 1970, Mechanism of the Chilean earthquake of May 21 and 22, 1960: Geological Society of America Bulletin, v. 81, p. 1001–1030.

Proctor, J., J. M. Anderson, S. C. L. Fogden, and H. W. Vallack, 1983, Ecological studies in four contrasting lowland rain forests in Gunung Mulu National Park, Sarawak: II. Litter fall, litter standing crop and preliminary observations on herbivory: Journal of Ecology, v. 71, p. 261–283.

Rindsberg, A. K., 1990, Freshwater to marine trace fossils of the Mary Lee coal zone and overlying strata (Westphalian A) Pottsville Formation of northern Alabama, *in* R. A. Gastaldo, T. M. Demko, and Y. Liu, eds., Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Geological Society of America, Southeastern Section, Field Trip Guidebook, p. 82–96.

Rex, G. M., and W. G. Chaloner, 1983, The experimental formation of plant compression fossils: Palaeontology, v. 26, p. 231–252.

Shute, C. H., and C. J. Cleal, 1987, Palaeobotany in museums: Geological Curator, v. 4, p. 553–559.

Stanley, D. J., and A. G. Warne, 1994, Worldwide initiation of Holocene marine delta by deceleration of sea-level rise: Science, v. 265, p. 228–231.

Stark, N., and C. F. Jordan, 1978, Nutrient retention by the root mat of an Amazonian rain forest: Ecology, v. 59, p. 434–437.

Staub, J. R., and R. A. Gastaldo, 2003, Late Quaternary incised-valley fill and deltaic sediments in the Rajang River Delta, *in* H. F. Sidi, D. Nummedal, P. Imbert, H. Darman, and H. W. Posamentier, eds., Tropical deltas of Southeast Asia—Sedimentology, stratigraphy, and petroleum geology: SEPM Special Publication 76, p. 71–87.

Staub, J. R., H. L. Among, and R. A. Gastaldo, 2000, Seasonal sediment transport and deposition in the Rajang River delta, Sarawak, east Malaysia: Sedimentary Geology, v. 133, p. 249–264.

Stephenson, R. A., J. Boerstoel, A. F. Embry, and B. D. Ricketts, 1992, Subsidence analysis and tectonic modeling of the Sverdrup Basin, *in* D. K. Thurston and K. Fujita, eds., Proceedings International Conference on Arctic Margins: Washington, D.C., Minerals Management Service, U.S. Department of the Interior, p. 149–154.

Stevanoviç-Walls, I. M., 2001, A paleontological study of an early Pennsylvanian forest preserved above the Blue Creek coal seam, Pottsville, Formation, northwestern Alabama: M.S. thesis, Auburn University, Auburn, Alabama, 98 p.

Stewart, W. N., and G. W. Rothwell, 1993, Paleobotany and the evolution of plants: Cambridge, United Kingdom, Cambridge University Press, 521 p.

Stout, J., 1980, Leaf decomposition rates in Costa Rican lowland tropical rainforest streams: Biotropica, v. 12, p. 264–272.

Tessier, B., A. W. Archer, W. P. Lanier, and H. R. Feldman, 1995, Comparison of ancient tidal rhythmites (Carboniferous of Kansas and Indiana, U.S.A.) with modern analogues (the Bay of Mont-Saint-Michel, France), *in* B. W. Flemming and A. Bartholomä, eds., Tidal signatures in modern and ancient sediments: International Association of Sedimentologists Special Publication 24, p. 259–274.

Thomas, W. A., 1968, Contemporaneous normal faults on flanks of Birmingham anticlinorium, central Alabama: AAPG Bulletin, v. 52, p. 2123–2136.

Thomas, B. A., 1986,The formation of large diameter plant fossil moulds and the Walton theory of compaction: Geological Journal, v. 21, p. 381–385.

Thomas, W. A., 1988, The Black Warrior Basin, *in* L. L. Sloss, ed., The geology of North America: Geological Society of America, v. D-2, p. 471–492.

Thomas, W. A., 1995, Diachronous thrust loading and fault partitioning of the Black Warrior foreland basin within the Alabama recess of the late Paleozoic Appalachian—Ouachita thrust belt: SEPM Special Publication 52, p. 111–126.

Thommeret, Y., J. Laborel, L. F. Montaggioni, and P. A. Pirazzoli, 1981, Late Holocene shoreline changes and seismotectonic displacements in western Crete (Greece): Zeitschrift Geomorphologie N.F. Supplement 40, p. 127–149.

Tjia, H. D., 1981, Examples of young tectonism in eastern Indonesia, *in* A. J. Barber and S. Wiryosujono, eds., The geology and tectonics of eastern Indonesia: Geological Resources and Development Centre Special Publication 2, p. 89–104.

Van Wagoner, J. C., R. M. Mitchum, K. M. Campion, and V. D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: AAPG Methods in Exploration Series 7, 55 p.

Ware, W. N., 2001, A paleoecological study of an in situ peat-forming Carboniferous forest in the Black Warrior Basin, Alabama: M.Sc. thesis, Auburn University, Auburn, Alabama, 81 p.

Weisenfluh, G. A., and J. C. Ferm, 1984, Geologic controls on deposition of the Pratt Seam, Black Warrior Basin, Alabama, U.S.A., *in* R. A. Rahmani and R. M. Flores, eds., Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists Special Publication 7, p. 317–330.

Whiticar, M. J., E. Faber, and M. Schoell, 1986, Biogenic methane formation in marsh and freshwater environments: CO_2 reduction vs. acetate fermentation-isotope evidence: Geochemica et Cosmochimica Acta, v. 50, p. 693–709.

Winston, R. B., 1990a, Coal paleobotany of the Mary Lee coal bed of the Pennsylvanian ''Pottsville'' Formation near Carbon Hill, Walker County, Alabama, *in* R. A. Gastaldo, T. M. Demko, and Y. Liu, eds., Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Geological Society of America, Southeastern Section, Field Trip Guidebook, p. 55–64.

Winston, R. B., 1990b, Preliminary report on coal quality trends in upper Pottsville Formation coal groups and their relationships to coal resource development, coalbed methane occurrence, and geologic history in the Warrior coal basin, Alabama: Alabama Geological Survey Circular 152, 53 p.

Winston, R. B., 1994, Models of the geomorphology, hydrology, and development of domed peat bodies: Geological Society of America Bulletin, v. 106, p. 1594–1604.

Zodrow, E. L., and C. J. Cleal, 1999, Anatomically preserved plants in siderite concretions in the shale split of the Foord Seam: Mineralogy, geochemistry, genesis (Upper Carboniferous, Canada): International Journal of Coal Geology, v. 41, p. 371–393.