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Eustatic and autocyclic influences on deposition of the lower Pennsylvanian Mary Lee coal zone, Warrior Basin, Alabama

T.M. Demko [a], R.A. Gastaldo [b]

[a] Morrison Research Initiative, Department of Earth Resources, Colorado State University, Fort Collins, CO 8052, USA

[b] Department of Geology, Auburn University, AL, 36849, USA

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Abstract

Deposition of marine strata associated with the Lower Pennsylvanian Mary Lee coal zone (Pottsville Formation) was controlled by the allocyclic mechanism of eustatic sea-level change. The vertical stacking of marine, marginal marine, and terrestrial facies indicates that this interval was deposited during a single transgression–regression–transgression cycle. Ravinement surfaces, and associated autochthonous macro-invertebrate and trace-fossil assemblages record the landward retreat of the shoreline and abrupt deepening due to rapid rise in sea-level. These horizons are overlain by terrigenous clastic facies, either tidal sand bodies or shelf mudstones, which indicate shoaling due to progradation during the subsequent filling of the generated accommodation space. Although marine influence, including the effects of tidal currents, continued during the more terrestrial phases of deposition, autocyclic factors, including the control of paleotopography by differential compaction of buried peat bodies, were also important in determining facies distribution.

1. Introduction

The role of autocyclic and allocyclic processes in the development of Carboniferous coal-bearing strata has been a source of considerable controversy. Autocyclic deltaic models, based on comparisons to the modern Mississippi delta, were developed for the northern and central Appalachian Carboniferous sequence (see summaries in Horne et al., 1978 and Ferm and Horne, 1979) and applied to contemporaneous deposits in the Warrior basin based on the assumption that similar lithofacies correlated with depositional facies (Ferm and Ehrlich, 1967; Ferm et al., 1967; Benson, 1982). These models

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were used to interpret the > 3000 m of Lower Pennsylvanian Pottsville Formation in the Warrior basin as having been deposited by delta-lobe switching, abandonment, and shallow-marine transgression due to compaction (Horsey, 1981; Benson, 1982; Mack et al., 1983). Water depths in the marine realm were envisioned as being no deeper than that documented in interdistributary bays, that is < 10 m (Cleaves and Broussard, 1980; Cleaves, 1981; Benson, 1982). The only nearshore marine facies (beaches, offshore bars, etc.) were believed to be restricted to the basal Pennsylvanian strata and these units were interpreted to represent barrier island deposits (Hobday, 1974).

Investigations during the past decade have demonstrated that nearshore sand bodies are not restricted to the basal Boyles sandstone. Tide-dominated sand bodies are documented above the Black Creek coal bed (Fig. 2) (Haas and Gastaldo, 1986) and the Ream coal (Demko, 1990). In addition, ravinement surfaces (Liu and Gastaldo, 1992) and fully marine macro-invertebrate communities (Gibson, 1990) are characteristic of lithofacies associated with these tidal sand bodies. This evidence requires a re-evaluation of the applicability of the delta-lobe switching model for marine, marginal marine, and terrestrial facies distribution within the basin. The purpose of this paper is to review and summarize recent work supporting our contention that both allocyclic and autocyclic processes play a significant role in the development of the Lower Pennsylvanian strata in the southern Appalachians.

2. Warrior basin

The Warrior basin is a triangular foreland basin of Carboniferous age located at the southern extremity of, and flanked on the southeast by, the folded and faulted Appalachian Orogen (Fig. 1). The basin is bounded on the north by the Nashville Dome and the Pascola Arch, and on the southwest by the deeply buried Ouachita orogenic belt (Thomas, 1989).

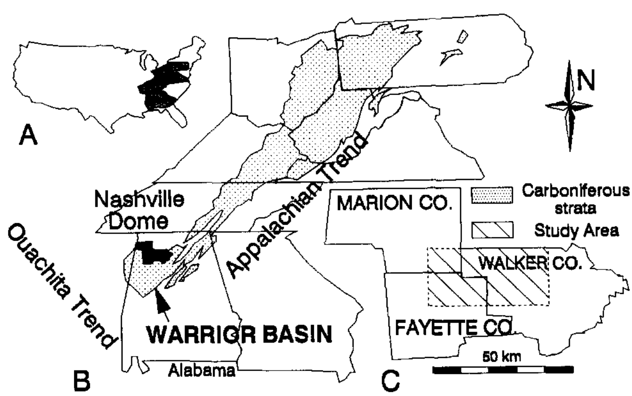

Fig. 1. Location map of study area. (A) Index map of U.S.A., (B) map of Carboniferous coal-bearing strata of Appalachians showing location of Warrior basin and study area, (C) location of study area in northwestern Alabama.

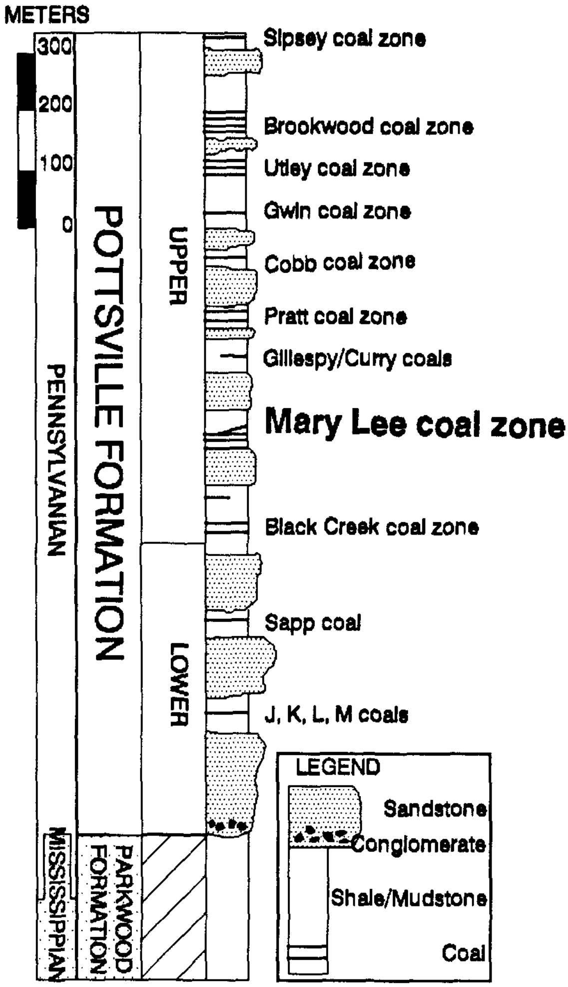

Fig. 2. Generalized stratigraphic column of the Pottsville Formation in the Warrior basin.

A southwest thickening wedge of Mississippian and Lower Pennsylvanian sedimentary rocks fills the basin. Carboniferous strata dip gently to the southwest approximately 0.5°, but increases in the subsurface to a few degrees farther to the southwest (Kidd, 1982). The Pennsylvanian section, the majority of which is assigned to the Pottsville Formation, is greater than 3000 m thick in the basin center (Hewitt, 1984). Subsidence, associated with foreland basin flexure basinward of the Appalachian thrust belt, created accommodation space for the entire section of Early Pennsylvanian age. The Pottsville Formation is composed of a cyclical alternation of shallow marine, nearshore, inshore, and terrestrial facies (Metzger, 1965; Pashin, 1991a). Terrestrial intervals in which one or more coal beds occur have been termed "coal zones" (Lyons et al., 1985), and presently ten coal zones, including the Mary Lee coal zone (Fig. 2) are recognized in the basin. To date, marine strata have been identified between the lowermost coal zones. No matter which time scale one utilizes (see discussion of Klein, 1990), the accumulation of these strata occurred over a relatively short geologic interval; the entire Pennsylvanian sequence is reported to be Westphalian A in age (Gillespie and Rheams, 1985). Demko and Gastaldo (1990) noted that sediment supply to any particular coastal depositional environment strongly influenced facies distribution laterally within and between coal zones. Sediment supply, in turn, was controlled by contemporaneous tectonic and climatic factors.

3. Stratigraphy and depositional environments of the Mary Lee coal zone

The Mary Lee coal zone, as defined by Gastaldo et al. (1991) contains, in ascending stratigraphic order, the Jagger, Blue Creek, Mary Lee, and Newcastle coal seams (Fig. 3). Lithofacies descriptions and interpreted depositional environments have been described in detail in previous publications (see Demko and Gastaldo, 1992; Liu and Gastaldo, 1992; Gastaldo et al., 1993). Therefore, the following discussion will be limited to a conspectus of the lithologies, stratigraphic sequence, and geographical distribution of the coal zone in northwestern Alabama. For the purposes of this discussion, we include within the Mary Lee coal zone and bounding marine strata those strata above the Ream coal ascending to below the Gillespie/Curry coals.

Some 1000 km^2 of outcrops are present in Warrior basin as surface mine highwalls, roadcuts, and natural exposures. These exposures extend laterally over several kilometers, sometimes in several oblique directions. This allows a three-dimensional view of the sedimentary facies architecture.

The oldest coal in the Mary Lee coal zone, the Jagger seam, is underlain by a fine- to medium-grained quartzose sandstone, informally called the Jagger sandstone (Fig. 3). The Jagger sandstone is presumably equivalent to the Nason sandstone of Pashin (1991b) and others. It is characterized by large-scale trough cross-stratification and is interpreted to have been deposited as series of tide-influenced, shore-parallel bars (Demko, 1990). Although the Jagger coal bed is fairly persistent throughout the study area, the thickness of the coal is variable, raging from 2.3–0.01 m over distances of less than a kilometer. These lenticular coal bodies are thickest in swales of the underlying Jagger sandstone and thinnest over ridges in the sandstone, which suggests compactional control on the paleotopography. The depositional environment of the Jagger coal is interpreted to have been a coastal mire.

The Jagger–Blue Creek interval is characterized by laminated sandstone and mudstone. Thickness of the interval ranges from 3–9 m. The depositional environments of this interval are interpreted to have been tidal flats and associated channels (Demko and Gastaldo, 1989; Demko and Gastaldo, submitted).

The Blue Creek coal bed overlies a root-worked horizon in the tide-influenced, interlaminated sandstone and mudstone below (Fig. 3). The Blue Creek is a continuous coal throughout the basin. It is consistently thin over the entire study area, varying little from 0.3 to 0.5 m. The interval between the Blue Creek coal and the Mary Lee coal (4–6 m) is typically mudstone with very fine-grained sandstone laminations. Locally, the interval is characterized by a coarsening-upward sequence of mudstone, mudstone

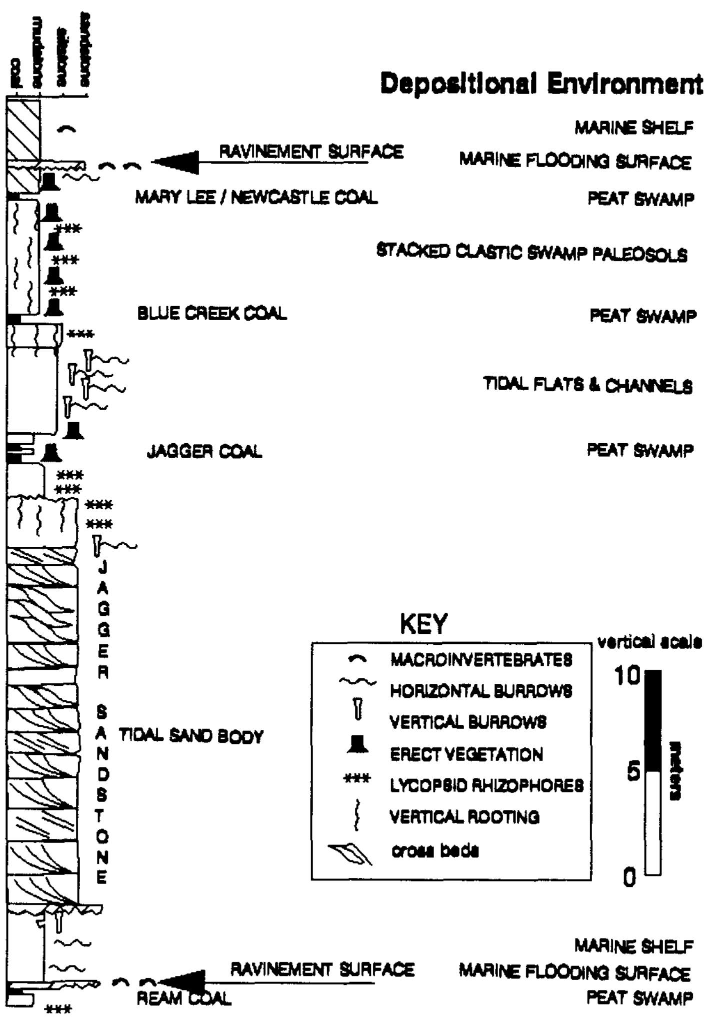

Fig. 3. Generalized stratigraphy and depositional environments of the Mary Lee coal zone.

with very fine-grained sandstone laminations and interbeds, and very fine-grained sandstone. Thin (> 2 m thick), broad (100–200 m wide) channel-form sandstone bodies occur locally within paleotopographic lows inherited from the underlying Jagger sandstone. These channels are interpreted to have been shallow creeks draining coastal lowlands. The Blue Creek–Mary Lee interval is also characterized by multiple fossil plant horizons which preserve erect and prone calamatean and lycophyte trunks, compressions of pteridosperm and lycophyte foliage, and the rooting structures *Stigmaria* and *Pinnularia*. These horizons mark the position of established vegetation in clastic swamps (sensu Gastaldo, 1987) (Demko and Gastaldo, 1990). The depositional environment of the Blue Creek–Mary Lee interval is interpreted to have been coastal, lowlying clastic swamps cut by shallow, broad creeks. These swamps did not accumulate any significant organic material because of clastic sediment influx due to local subsidence caused by compaction of the buried Blue Creek peat.

The Mary Lee coal bed rests immediately over the last clastic swamp horizon in the Blue Creek–Mary Lee interval (Fig. 3). The Mary Lee coal occurs over the entire study area and continues south into the deeper portions of the basin (Thomas and Womack, 1983). However, the seam varies widely in quality and thickness. In the extreme western portion of the study area, the Mary Lee coal horizon consists of two benches (1.0–1.5 m thick) of interbedded, coalified lycophyte logs and mudstone, separated by a mudstone parting (0.5 m thick). In this area the Mary Lee is high in ash (45%) and sulfur (6.5%) content (Eble et al., 1994). Eastward, these benches merge into one coal seam with many thin sandstone and mudstone partings. One sandstone parting represents a channel belt that splits the Mary Lee into a thick upper bench (0.5–0.7 m) and a thin lower bench (0.2–0.3 m). In this area, the Mary Lee is lower in ash (10%) and sulfur (< 1%) content than the seam is to the west (Eble et al., 1994). Although the channel sandstone pinches out eastward, the seam splits once again. The upper bench is locally known as the Newcastle seam. The depositional environments of the Mary Lee/Newcastle coal horizon are interpreted to have been autochthonous mires and contemporaneous fluvial channel and overbank environments with some tidal influence (Liu, 1990). There is a ravinement surface above the Mary Lee/Newcastle coal bed, marking a marine transgression (Liu and Gastaldo, 1992).

The vertical succession of facies within the Mary lee coal zone records deposition in the following sequence of settings: (1) tide-influenced shelf/lower shoreface; (2) discontinuous, coastal mires, clastic swamps, and tidal mudflats; (3) mires and aggrading clastic swamps; (4) mires and tide-influenced fluvial/deltaic deposits and (5) brackish lagoon to marine shelf (Fig. 3). This sequence reflects terrigenous sedimentation along a tide-influenced coastal zone during a single transgression–regression–transgression cycle.

4. Evidence of allocyclic influences

4.1. Autochthonous macro-invertebrate and trace fossil assemblages

One feature of the Warrior basin noted by many previous workers is the paucity of macro-invertebrate assemblages. Metzger (1965) identified only four macroinvertebrate horizons in his subdivision of the Pottsville Formation, and believed that this was an accurate reflection of prevailing conditions (overwhelmingly terrestrial, in his view) at the time of deposition. Gillespie and Rheams (1985) generally concurred with the findings of Metzger (1965), although they increased the number of identified macro-invertebrate horizons to ten. Garbish and Dewey (1989) found more marine macro-invertebrate assemblages in sections previously thought to be terrestrial in origin. The increase in frequency of occurrence is based primarily upon the recognition of stunted and juvenile forms in once interpreted "barren" shale intervals. These depauperate faunas also have been recognized in the Plateau coal field, in time-equivalent rocks northeast of the study area (Gibson, 1985; Gibson and Gastaldo, 1987).

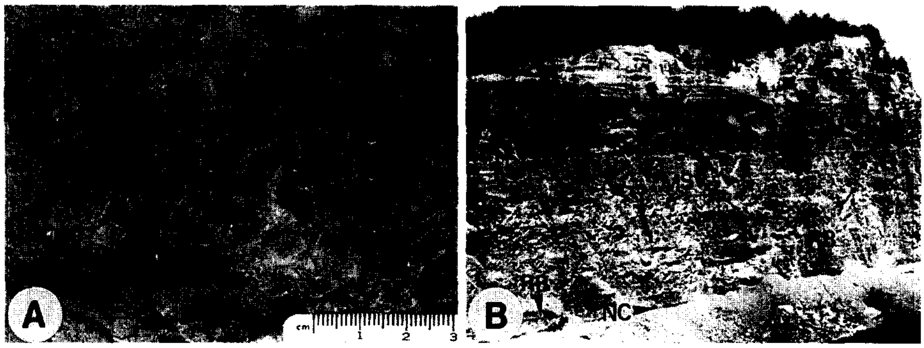

Fig. 4. (A) Autochthonous marine macroinvertebrates from immediately above the ravinement surface above the Mary Lee coal bed, *P* productid bivalve; (B) Outcrop of thick mudstone (*MS*) above ravinement surface (*RB*) above Newcastle coal bed (*NC*).

Typical Carboniferous marine trace fossils, on the other hand, were first recognized only within the past decade (Garbish and Dewey, 1989; Rindsberg et al., 1989; Rindsberg, 1990), and until very recently (Rindsberg, 1990), were not used to interpret paleoecological settings. The presence of a wide diversity of these trace fossil forms is a characteristic of a variety of substrate and salinity conditions.

The significance of the stratigraphic position and distribution of specific faunal assemblages have only recently been addressed. Both concentrated and dispersed faunal assemblages are preserved in the marine strata bounding the Mary Lee coal zone, although there is a distinct compartmentalization (Gastaldo et al., 1991). High-diversity, fully marine assemblages characteristic of an offshore, open-shelf setting, including bivalves, gastropods, brachiopods, trilobites, and echinoderm stem ossicles are concentrated in thin beds interpreted as primary biogenic concentrations (Liu and Gastaldo, 1992) (Fig. 4A). The high diversity and concentration of bioclastic elements are due to a paleogeographic position far enough offshore such that the locus of clastic sediment influx was far enough removed to allow the proliferation of benthic, filter-feeding organisms. Articulated juvenile and adult brachiopods and bivalves co-occur in these assemblages, indicating that an established regenerative community existed in the substrate. These organisms require quiet waters, normal salinities, and relatively stable substrates. In effect, the waters in these offshore sites must have been relatively free of suspended, fine-grained, clastic sediment, some distance away from the influence of fresh-water pulses, and in a location where depositional rates were low. These conditions were essential for the survival of these organisms.

The diversity of ichnofauna in the concentrated zones is difficult to fully document because the substrates were almost completely bioturbated. Where trace fossil forms can be identified, both *Zoophycos* and *Teichichnus* are very common. Homogenization in this marine environment reflects substrate use by either a large number of individuals over time (higher relative diversity or greater population) or an indeterminate number of individuals over a longer period of time (low? relative diversity, condensation and time-averaging).

The only geographical position where such situations could exists is distal to the shoreline, kilometers away from the debouchment of terrigenous sediment and several tens of meters below wave base. The only way to provide such a deep-water setting superimposed upon terrestrial deposits is through a dramatic, rapid increase in water depth due to sea-level rise.

Depauperate elements of the fauna, on the other hand, are found scattered throughout the thick mudstone sequences (Fig. 4B) above and below coal zones. There is a dramatic reduction in systematic diversity of macro-invertebrates preserved within these facies. Orbiculoid brachiopods and nuculid bivalves predominate. Orbiculoids are epiphytic taxa that lived under brackish and/or fluctuating salinities (Gibson and Gastaldo, 1987), whereas the nuculids are thin-shelled taxa that lived just beneath the sediment–water interface as a strategy to survive stressful conditions. No widespread in-habitat macro-invertebrate assemblages have been identified in these units. Individuals are small, some representing either juveniles or stunted forms. Such stress may be initiated by increasing turbidity, higher sedimentation rates, and/or increasing freshwater discharge resulting in salinity fluctuations. The thick marine mudstones and dispersed, low diversity macrofaunal assemblages above the concentrated assemblages that directly overlie coal zones, indicate a change in conditions. This change reflects increased turbidity, sedimentation rates, and fluctuating salinities due to increased localized terrigenous sediment load.

This same change is also reflected in the preserved trace-fossil assemblages. Bioturbation is minimal, primary sedimentary structures are essentially undisturbed, and trace fossils occur as discrete horizontal, shallow burrows (*Planolites*, *Olivilites* and *Scalarituba*). To date, no tiering hierarchy of trace fossils has been identified within these lithofacies. We infer the absence of tiering to be related to the higher rates of sedimentation and unstable substrate conditions.

The only geographical positions where such a situation exists is proximal to the shoreline where debouching sediment plumes are active and water depths decrease due to rapid sedimentation. This reflects progradation of nearshore facies into deeper water. The establishment of wetland paleosols above these marine rocks attests to the regressive character of these deposits.

4.2. Ravinements

By itself, the superposition of nearshore facies over terrestrial facies by the process of landward shoreface migration can not be used as evidence for an autocyclic or allocyclic mechanism for transgression. The landward migration of a shoreline and the creation of a ravinement surface can be the result of either localized sea-level change due to delta-lobe abandonment (Penland et al., 1988) or eustatic sea-level change and transgression of coastal facies along a coast line (Swift, 1968). A clear indication of the cause for ravinement is reflected in the areal extent over which erosion can be traced. Shoreface retreat on the order of kilometers is considered to be a response to regional or global sea-level rise (Everts, 1987).

Although the superposition of marine facies over terrestrial facies has long been recognized in Carboniferous coal-bearing sequences, the recognition and description of ravinement surfaces has only recently come about (Joeckel, 1989; Liu and Gastaldo, 1992). The documentation that the ravinement surface above the Mary Lee coal zone

Fig. 5. Ravinement surface (*RS*) truncating tidal channel deposits above the Mary Lee (*ML*) and Blue Creek (*BC*) coal beds. A ravinement bed (*RB*) overlies the ravinement surface.

ranges over a geographical area of > 1800 km^2 and along a transgressive track of more than 60 km has been used as evidence for eustatic sea-level change rather than a local change due to tectonic activity (Liu and Gastaldo, 1992; Gastaldo et al., 1993) (Fig. 5).

The ravinement surface identified below the Mary Lee coal zone is physically and paleontologically similar to the one above the coal zone identified by Liu and Gastaldo (1992). Because the physical and paleontological features are comparable, we believe that they were formed by similar processes, even though the ravinement surface below the Mary Lee coal zone has limited outcrop exposure. Additional data that can be used to support the development of this surface in response to a regional transgression include the superposition of a thick (> 20 m) marine sand body above this surface.

4.3. Tidal sand bodies

The Jagger sandstone is a fine- to medium-grained, quartzose, sublitharenite (Thomas and Womack, 1983; Raymond et al., 1988). It is 3.5–29 m thick and is characterized by large-scale trough cross-bedding, symmetrical and asymmetrical ripples, reactivation surfaces and soft-sediment deformation features (Fig. 6). Cross beds are separated by thin drapes of phytoclasts, medium- to coarse-grained muscovite flakes and silty

Fig. 6. Large-scale trough cross beds and tidal bundles in the Jagger sandstone.

mudstone. Paleocurrent directions, as measured from cross beds, are to the south-southwest (mean paleocurrent direction 193°; $n = 195$). A thin (< 0.1 m) zone containing pebble-sized siderite and mudstone clasts typically occurs at the base of the unit, indicating some scour into the underlying and peripheral mudstone.

Sigmoidal tidal bundling of cross strata, reactivation surfaces, and mud drapes in this unit are evidence of tidal influence (Demko and Gastaldo, 1989; Demko and Gastaldo, submitted). Thickness trends in the sandstone, and the intervals above, indicate that the geometry and paleotopography of the sand body influenced facies distribution in the overlying sequence until the accumulation of the Newcastle coal (Demko, 1990). Paleotopographic lows can be identified by the Jagger sandstone thicknesses (3–5 m), thick Jagger coal (> 1 m) and Jagger–Blue Creek intervals (8–10 m). Over paleotopographic highs (sandstone thicknesses 15–29 m) the Jagger coal thins to less than 0.5 m and the Jagger–Blue Creek coal interval thins to less than 4 m.

On the basis of isopach maps of the thicknesses of quartzose sandstone, lithic sandstone and coal zones/cycles in the Upper Pottsville, Pashin (1991b) has interpreted the trend of the paleoshoreline to have been roughly northeast–southwest, with landward having been to the southeast. The thickness trend of the Jagger sandstone parallels this northeast–southwest trend.

The Jagger sandstone is interpreted to have been deposited as nearshore, shore-parallel sand bodies (Demko and Gastaldo, 1990; Demko and Gastaldo, submitted). Tidal bundling of cross strata, tidal reactivation surfaces, mud drapes and bi-directional paleocurrent directions within this unit are consistent with deposition within a tide-influenced (sub-tidal) environment. Superposition of the sandstone bodies above marine and brackish mudstones reflects an inner shelf setting. However, the tidal-current dominated cross bedding throughout the unit, and wave ripples in the upper part, imply a nearshore, possibly lower shoreface, environment.

4.4. *Tidal flats*

The Jagger–Blue Creek interval consists of a coarsening-upward sequence of mudstone, interlaminated mudstone and very fine-grained sandstone. Primary sedimentary structures associated with the interlaminated mudstone and sandstone include: (1) horizontal, parallel bedding; (2) micro-scale cross-laminations; (3) tool marks; (4) rill marks; (5) ripples; (6) raindrop imprints and (7) soft-sediment deformation features (micro-faulting and load structures) (Fig. 7). Paleocurrent indicators (current ripples, oriented plant material and tool marks) indicate drainage to the south. Rhythmic lamination in this interval has been interpreted to reflect neap-spring tidal cyclicity (Demko et al., 1991; Demko and Gastaldo, submitted). Fossils preserved in this facies include trace fossils, phytoclasts, and rare plant macrodetritus (allochthonous lycophyte leaves and calamitean stems). Ichnofossils include shallow horizontal burrows (*Haplotichnus*, *Palaeophycus* and *Treptichnus*), vertical (*Rosselia*) and resting burrows (*Lingulichnus* and *Lockiea*), surface trails (*Kouphichnium*, other arthropod and amphibian trackways), and grazing traces (Rindsberg, 1990; Demko and Gastaldo, 1989).

The interlaminated mudstone and sandstone, and very fine-grained sandstone facies in the Jagger–Blue Creek interval, have been interpreted to have been deposited in an

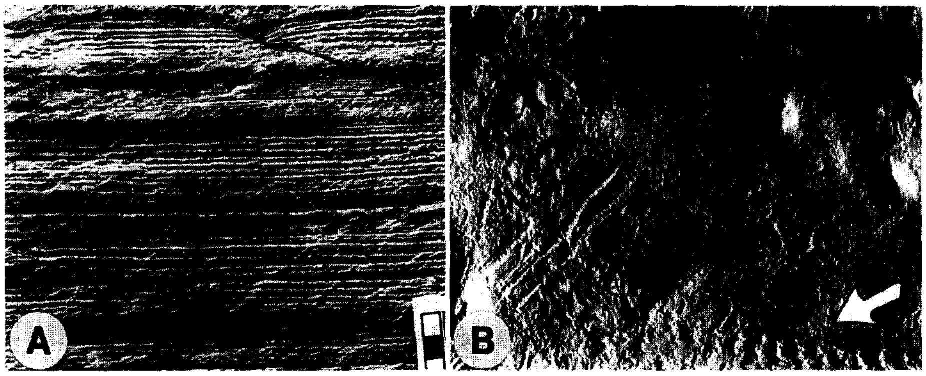

Fig. 7. Tidal flat facies above Jagger coal bed. (A) Rhythmic laminations recording neap-spring cyclicity. Scale subdivided in cm; (B) Typical arthropod trackway commonly found in tidal flat facies, arrow is 3 cm long.

inshore, fresh-to-brackish, tidal-flat environment, possibly in the upper reaches of estuaries. A similar facies is locally present between the Mary Lee and Newcastle coal beds.

5. Evidence of autocyclic influence

Although the above lines of evidence support the allocyclic influence of both eustatic sea-level change and tidal currents, we do not totally discount autocyclicity as an influence on sedimentation. We have also documented the localized influence on paleotopography by the compaction of buried peat as an important autocyclic mechanism that controlled facies distribution in the more terrestrial sections of the Mary Lee coal zone.

5.1. Stacked clastic swamps and mires

The Blue Creek–Mary Lee interval is characterized by multiple fossil-plant horizons. There are three to five of these zones preserved, the number generally dependent on the thickness of the interval. These horizons mark the position of established vegetation in clastic swamps (Demko and Gastaldo, 1992). This interval has been interpreted as a series of stacked clastic swamp paleosols (entisols) based on the presence of: (1) autochthonous, erect, lycophyte and calamitean trunks; (2) mud-cast, prostrate, parautochthonous, lycophyte and calamitean trunks; (3) compression–impression assemblages of autochthonous to parautochthonous pteridosperm and lycophyte foliage, branches and reproductive structures; (4) autochthonous axes and helically arranged lateral appendages of *Stigmaria* and *Pinnularia* and (5) siderite nodules associated with rooting structures and other plant material (Fig. 8). Erect trunks rooted in the uppermost clastic swamp of the series often terminate in the overlying Mary Lee coal, indicating that this swamp was the progenitor to the Mary Lee mire. The depositional environment

Fig. 8. Stacked clastic swamp facies between Blue Creek (*BC*) and Mary Lee (*ML*) coal beds; (*L*): erect lycophyte trunks; Y. Liu for scale.

of the Blue Creek–Mary Lee interval is interpreted to have been coastal, low-lying clastic swamps with broad, shallow drainage channels.

Catastrophic burial of the Blue Creek mire by mud from high-magnitude flood events terminated peat accumulation. A clastic swamp environment was formed when the new sediment surface was colonized by vegetation suited to growth on mineral soils. Some surviving elements of the mire vegetation may also have played a role in the new community. Compaction of the buried peat created a depositional low, allowing continued accumulation of flood deposits that buried the clastic swamp vegetation. This process of punctuated loading, compaction and subsidence, and recolonization by clastic swamp vegetation, continued until the buried Blue Creek peat reached relative compactional stability. At this point, the clastic swamp forest floor could begin to accumulate organic material. A high water table, indicated by gley features in the paleosols and evidence of tidal influence in the swamps (Gastaldo, 1992), and a stable sediment surface, created conditions amenable to the resumption of peat accumulation and formation of the Mary Lee mire.

6. Discussion

The nature of cyclic deposits (''cyclothems'') within Carboniferous coal-bearing sequences has been the focus of hypothesis generation and testing for application of one or the other end-member of the spectrum [e.g., delta models (Horne et al., 1978; Ferm and Horne, 1979) vs. transgression–regression hierarchy (Busch and Rollins, 1984)]. As with most controversies, the answer most likely lies somewhere within the continuum between these extremes (for example Belt and Lyons, 1989). We believe this is particularly true for the Lower Pennsylvanian of the Warrior basin.

If we are to consider the autocyclic end-member of the continuum, we would expect several obvious stratigraphic and paleoecologic relationships to prevail in the basin. According to the autocyclic tenet, localized interdistributary bays develop as debouchment of clastic sediment shifts from one delta lobe to another. The abandoned delta lobe undergoes compaction and continued subsidence, providing new accommodation space for interdistributary bay facies, and eventually, the avulsion and superposition of a new delta lobe. The amount of compaction of the delta lobe sediments would control the thickness of interdistributary bay facies that could accumulate before recolonization by pioneering wetland vegetation. This results in very thin interdistributary bay sequences. Localized transgression over abandoned delta lobes can occur by landward shoreface migration (Penland et al., 1988). Compaction of delta lobe sediments accompanied by landward shoreface migration could increase the potential accommodation space, but only slightly more than wave base (no more than 10 m and generally less than 5 m). In this case, the accommodation space is filled by nearshore shelf sediments rather than interdistributary bay deposits. This would result in a geographically localized interplay of terrestrial and marine facies due to contemporaneous sedimentation in active and abandoned delta lobes along the shoreline. The distribution of invertebrate faunas along these types of deltaic shorelines would reflect salinity gradients from fully marine to brackish conditions and differing turbidities. Fossil invertebrate assemblages in these types of deposits would also reflect time-transgressive changes in physical conditions. Terrestrial and marine facies and communities would be regionally time-equivalent along the shoreline. Continued subsidence and accumulation of deltaic deposits would result in a complex mosaic of spatially restricted, but laterally and temporally equivalent lithofacies and biofacies.

If we consider the allocyclic end-member of the spectrum, then we would expect a different set of stratigraphic and paleocologic relationships to prevail. Rapid sea-level rises during the Early Pennsylvanian, due to ice-sheet dynamics in the continental ice sheet in Gondwana (Veevers and Powell, 1987), would have resulted in the basin-wide superposition of discordant nearshore facies over fully terrestrial or estuarine deposits. Interdistributary bay facies, if found, would have been localized in the basin in a position proximal to the farthest landward point of the shoreline migration. Thick, regionally extensive bay deposits could not be formed under these conditions. Glacio-eustatic sea-level rise would result in the rapid establishment fully marine conditions rather than a slow evolution from fully terrestrial to fully marine. Such a dramatic change in physical conditions should be reflected in the benthic invertebrate communities as influenced by relative rate and tempo of deposition.

The character and geographic distribution of ravinement beds, macro-invertebrate and trace-fossils assemblages and thick nearshore sand bodies are indicative of regional-scale processes rather than those operating on a local site. The ravinement surface above the Mary Lee and Newcastle coal beds can be traced as a nearly horizontal plane both in the surface and subsurface of northwestern Alabama. The lithology of the units immediately overlying the erosional surface are variable across the area, resulting from shoreface reworking of older, heterogeneous paralic deposits. The ravinement bed, then, reflects variability within the local source rather than changes in local sediment supply. And, although the macro-invertebrate assemblage preserved within the ravinement bed varies across the 1800 km^2 study area, this variability is a function of substrate composition rather than salinity and turbidity (Liu and Gastaldo, 1992). These two features, then, support an allocyclic interpretation (eustatic sea-level rise) for the genesis of the marine strata rather than an autocyclic mechanism (delta-lobe abandonment). In addition, the presence of thick, nearshore, tidally-influence sand bodies, and the thick regressive shales overlying ravinement beds, represents the ''shoaling-upward'' fill of accommodation space generated by rapid sea-level rise.

We believe, though, that allocyclic mechanisms are not solely responsible for basin-wide facies distribution. Based on our field area, we cannot account for autocyclic processes operating contemporaneously with allocyclic sea-level rise. That is because any sediments bearing evidence of possible autocyclic control on deposition might have been removed during landward migration of the shoreface. To date, autocyclic influence on the depositional character of the marine strata in the basin has not been documented. However, our studies and others have documented the strong autocyclic control of facies distribution in the terrestrial paralic facies in the basin.

7. Summary and conclusions

The development of the marine-influenced facies associated with the Mary Lee coal zone was controlled principally by the allocyclic mechanisms of eustacy and tides. Autochthonous marine macro-invertebrate assemblages and typical marine trace fossils are preserved immediately above ravinement or marine-flooding surfaces below the Jagger sandstone and above the Mary Lee/Newcastle coal bed (Fig. 3, 4). These horizons mark an abrupt deepening, superimposing open-marine, clear-water facies over paralic and tidal flat/channel facies (Fig. 5). The lithologic character of these horizons indicated that they were formed by the rapid landward movement of the shoreface over a low gradient coastal plain (Liu and Gastaldo, 1992). Truncation of underlying facies indicated that some erosion was involved with this process (Liu, 1990). Quartzose sand bodies, deposited on an energetic, tide-swept shallow shelf are present above the lower transgressive facies (Fig. 6), while a thick mudstone sequence with a preserved depauperate, marine to brackish-water fauna is present above the upper transgressive facies (Fig. 4B). These two facies record the return to terrigenous clastic sediment deposition during the subsequent regression and progradation of terrestrial facies. The differences between these two intervals possibly record a change in sediment source area, the quartzose sand sandstones in the lower interval having been derived from the northeast (Demko, 1990), while the mud-dominated facies in the upper interval prograded from the southeast (Pashin, 1991b). Tidal flat and tidal channel facies identified within the coal zone indicate that marine influence continued during regression (Fig. 7).

The development of the most terrestrial facies in the coal zone, clastic swamps and mires, however, was affected by autocyclic mechanisms inherent to the local depositional system. The compaction of buried peat bodies controlled the rate of clastic sediment influx into vegetated swamps, and determined whether these areas would accumulate organic material or be susceptible to burial by floods (Demko and Gastaldo, 1992).

In conclusion, we believe that eustatic sea-level change was dominant allocyclic factor in controlling the deposition of marine strata associated with the Mary Lee coal zone. The overall stacking pattern of marine and terrestrial facies indicates that the coal zone was formed during a single transgression–regression cycle. However, allocyclicity alone cannot account for all of the sedimentological characteristics of this interval. Autocyclicity, in the form of compactional control of paleotopography was the dominant factor in facies distribution in the most terrestrial facies.

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