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Application of sequence and genetic stratigraphic concepts to Carboniferous coal-bearing strata: an example from the Black Warrior basin, USA

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Abstract Carboniferous strata provide an excellent example on which to test the application of genetic stratigraphic and sequence stratigraphic concepts. Both approaches are employed in the evaluation of the coal-bearing strata of the Black Warrior basin, south-eastern USA. Bounding hiatal surfaces have been recognized in the succession of rock that includes the Mary Lee coal zone. Within the framework of genetic stratigraphy, one genetic sequence has been identified comprised of offlap (progradational and aggradational facies) and onlap (aggradational and transgressive facies) components. Seven parasequence sets have been delimited according to the concepts of sequence stratigraphy. These have been ascribed to transgressive, highstand and shelf margin systems tracts. The identification of components of these contrasting frameworks provide the basis for evaluating other Carboniferous strata.

Key words Sequence stratigraphy – Coal-bearing strata – Black Warrior basin, USA

Introduction

Cyclical sedimentation has long been recognized in the Carboniferous rocks of Euramerica (Udden, 1912; Weller, 1930; Wanless and Shepard, 1936). Pennsylvanian 'cyclothems', involving the alternation between terrestrial and marine strata, have been interpreted to represent regressive and transgressive deposition, respectively. A variety of autocyclic (intrinsic) and allocyclic (extrinsic) mechanisms have been proposed as mediating factors to explain this pronounced cyclicity (for a current review, see Riegel, 1991). Recent discussions have interpreted concurrent tectonic and climatic processes as controls of cyclothem deposition (e.g. Klein and Willard, 1989; Read and Forsyth, 1989; Cecil, 1990; Klein and Kupperman, 1992).

Although it would seem that these Carboniferous rocks would be ideal strata in which to test the applicability of sequence (Van Wagoner et al., 1988; 1990) and genetic (Galloway, 1989) stratigraphic concepts, this has not been so. Most attention has been focused on the applicability of such models to marine and marginal marine Cretaceous rocks where transgressions, characterized by ravinement surfaces, have been recognized (e.g. Weimer, 1984; Bergman and Walker, 1987; Cross, 1989). The utilization of these bounding surfaces for regional correlation has become the basis for identifying intervals of progradation punctuated by periods of transgression within basins. Only recently have ravinement surfaces been identified (Joeckel, 1989; Gastaldo et al., 1990) and characterized (Liu and Gastaldo, 1992) in Carboniferous strata. Their recognition is one of several fundamental parameters important in understanding and interpreting Late Palaeozoic basin histories. Additionally, with the ability now to identify sequence boundaries comparable with those in other parts of the rock record, the applicability of sequence and genetic stratigraphic concepts to the Carboniferous can be demonstrated.

Overview of Black Warrior basin

The Black Warrior basin is a triangular foreland basin of Carboniferous age that is exposed in northern Alabama and buried beneath Cretaceous Coastal Plain deposits in north-eastern Mississippi. It is located at the southern extremity of, and flanked on the south-east 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 south-west by the deeply buried Ouachita orogenic belt (Thomas, 1989).

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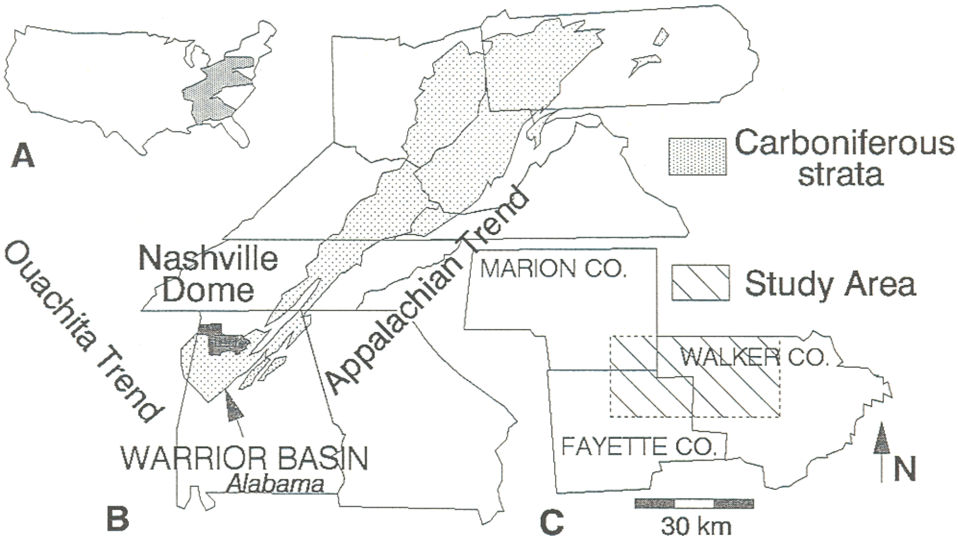
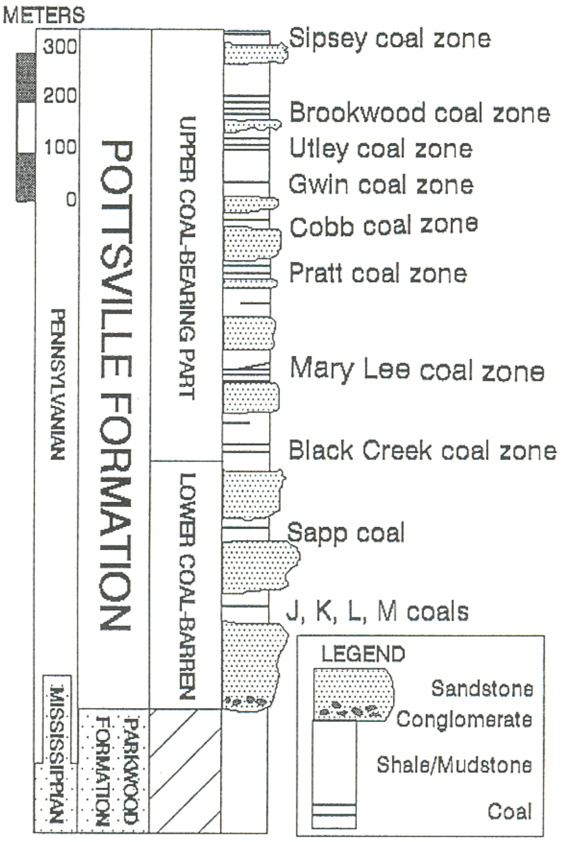
Fig. 1. **(A)** Geographical position of eastern USA in which Carboniferous rocks occur. **(B)** Distribution of Carboniferous strata illustrating the geographical position of the Black Warrior basin. **(C)** Location of present study in north-western Alabama



A south-westwards thickening wedge of Mississippian and Lower Pennsylvanian sedimentary rocks fills the basin. Carboniferous strata dip gently to the south–south-west at an angle of approximately 0.5°, but the dip angle increases to a few degrees in the subsurface farther to the south-west (Kidd, 1982). The Pennsylvanian section, most of which is assigned to the Pottsville Formation, is greater than 3 000 m thick in the centre of the basin (Hewitt, 1984). It thins northwards due to both depositional thinning and post-Carboniferous erosion. Subsidence, associated with foreland basin flexure basinwards of the Appalachian thrust belt, created accommodation space for the entire Pennsylvanian section. It is composed of cyclical alternation of shallow marine, nearshore, inshore and terrestrial facies (Metzgar, 1965; Pashin et al., 1990). Terrestrial intervals in which coal occurs have been termed coal zones (after Lyons et al., 1985), and nine coal zones are presently recognized in the basin. To date, marine strata have been identified between the lowermost coal zones. No matter which time-scale is prefered (see discussion of Klein, 1990), the accumulation of these strata occurred over a relatively short geological interval; the entire Pennsylvanian is reported to be Westphalian A in age (Gillespie and Rheams, 1985). Demko and Gastaldo (1992) note 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 orographic, climatic and hydrological parameters operating contemporaneously.

Our investigations have focused on one specific coal zone, the Mary Lee coal zone, and the subjacent and suprajacent rocks (Fig. 2). The Mary Lee coal zone is economically the most productive in the basin, being mined in the surface and subsurface during the past century. In addition, it is the target for coal bed methane production and feasibility studies (Pashin et al., 1990). The Mary Lee coal zone is exposed in natural outcrop, mine highwalls and road cuts in an area over 1 000 km^2 within Walker and Fayette Counties, north-western Alabama (Fig. 3). Extensive mining has been conducted throughout this area, resulting in exposures that often extend several hundreds to over a thousand metres laterally. Frequently, portions of highwalls are oriented oblique or perpendicular to each other, providing a three-dimensional view of the stratigraphic sequence. In addition, subsurface data are available from local mining companies and the Alabama Geological Survey (through the USGS KRCRA drilling programme).

Fig. 2. Generalized stratigraphy in the Black Warrior basin indicating the nine recognized coal zones. The Mary Lee coal zone, the most economically productive, is the focus of the present study



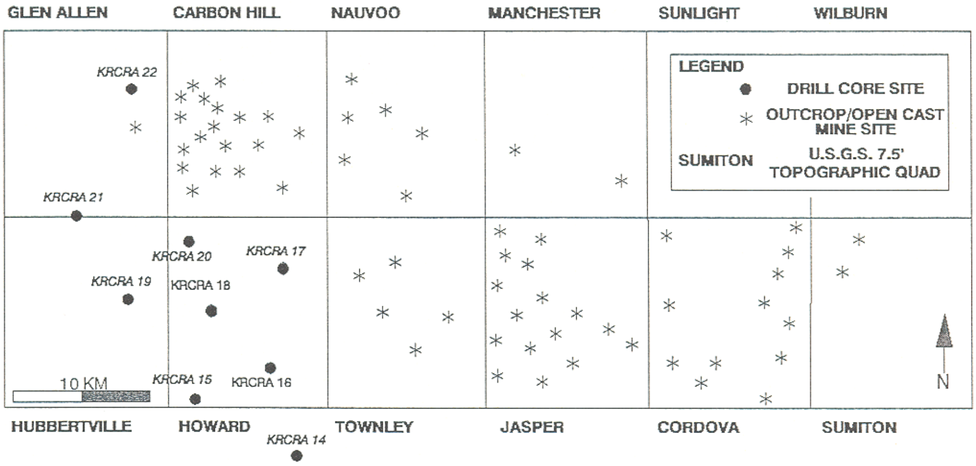


Fig. 3. Distribution of the Mary Lee coal zone in Walker and Fayette counties, Alabama. Outcrop, mining operations and drill core sites. USGS KRCRA (Known Recoverable Coal Resource Availability Programme cores) are indicated within US Geological Survey Topographic Quadrangles

Mary Lee coal zone stratigraphy and facies interpretation

Traditionally, the Mary Lee coal zone contains, in ascending stratigraphic order, the Ream, Jagger, Blue Creek, Mary Lee and Newcastle coal seams (Raymond et al., 1988). Gastaldo et al. (1990) consider the Ream coal to represent a distinctive coal zone developed beneath the Mary Lee coal zone. Therefore, the following discussion will focus on the interval beginning with the informally named 'Jagger bedrock' (= Nason Sandstone; Pashin et al., 1991) and ending with the overlying Morris Shale (Fig. 4). Arguments to support the segregation of the Ream coal into a separate coal zone will be presented later.

'Jagger bedrock' sandstone

A thick, fine- to medium-grained sublitharenite underlies the geographically restricted Jagger coal seam. The sandstone body is regionally isolated in the north-western sector of the basin. Isopach maps of the sandstone reflect an elongate body oriented north-east – south-west, along the inferred palaeo-shoreline. The base of the sandstone is erosional and in discomformable contact with an underlying bioturbated, fossiliferous shelf mudstone. The 'Jagger bedrock' is characterized by large-scale trough cross-stratification (largely trough, but some tabular, cross-bedding with sets and cosets defined by truncation and reactivation surfaces), rippled bedding, and soft sediment deformation features (overturned or parabolic, recumbent cross-bedding and slumping; Fig. 5). Primary cross-bed dip directions are oriented to the south-east and south-west (Demko and Gastaldo, in preparation), directed towards the inferred land (Ferm and Ehrlich, 1967). Large dune and sand wave-like megaforms occur on the top of the sandstone body and are manifested as 'rolls' in the pit floors of surface mines where the Jagger coal seam is exploited (Demko, 1990). Tidal bundling of cross strata, tidal reactivation surfaces, mud drapes and bipolar palaeocurrent directions are all indicative of deposition within a tide-influenced environment. The trough cross-stratification is interpreted as the result of the migration, accretion and aggradation of flood tide-driven subaqueous dunes over a shallow, muddy shelf. Ebb-tidal influence was minimal, only reworking and rippling the foresets of these large bedforms. The 'Jagger bedrock' is interpreted as representing subtidal, shore-parallel bars (Demko and Gastaldo, in preparation).

Jagger coal

The Jagger coal seam occurs only immediately above the sandstone and, therefore, is restricted in its geographical distribution. Stigmarian rhizophores and appendages ('rooting structures' of arborescent lycophytes) penetrate the top of the 'Jagger bedrock', and pedogenic features, including colour mottling, siderite glaebules and slickensides are common (Demko and Gastaldo, in preparation). These rooting structures either originated from initial colonization of the sandstone or from peat swamp vegetation. The coal occurs as lenticular bodies with variable thickness. Thicknesses range from 2.3 m to only a few centimetres over a distance of less than a kilometre, with the thickest coal occurring in the swales of the underlying sandstone. The thinnest accumulations occur over sandstone ridges. A persistent carbonaceous mudstone parting splits the seam into a thick lower and thin upper bench. Two erect autochthonous forests, composed of arborescent lycophytes (club mosses), are preserved immediately above the thickest coal. The first forest is preserved at the top of, and rooted within, the coal. Trees are moulded and cast by mudstone, and forest litter is preserved as an adpression assemblage. The second forest occurs approximately 0.5 m above the first forest, preserved similarly although a well developed forest litter assemblage is missing. Erect trunks are moulded and cast by the lithologies of the overlying Jagger – Blue Creek interval. The Jagger coal is interpreted to have been an autochthonous peat mire buried by alluvium, with subsequent recolonization by lycophytes in a weakly developed hydric soil (Demko and Gastaldo, in preparation).

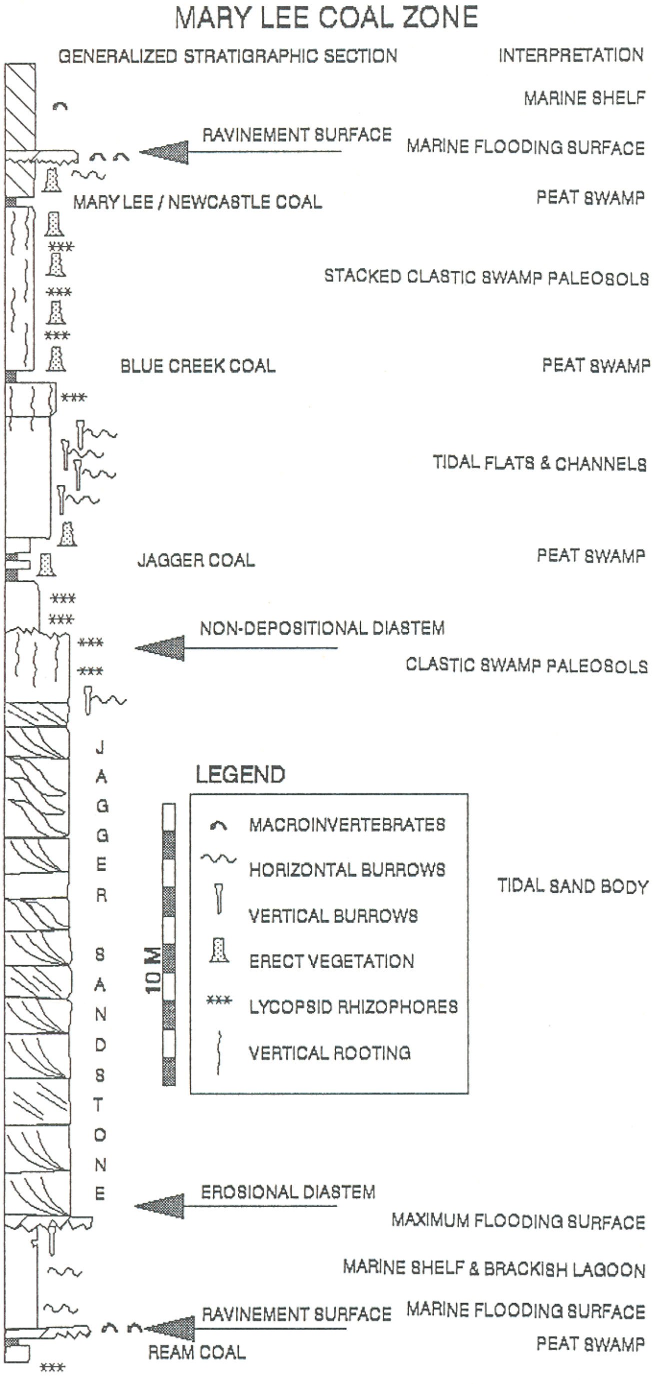


Fig. 4. Generalized stratigraphic section of the Mary Lee coal zone reconstructed using outcrop, mine highwall and subsurface core data. Interpretations for each environment of deposition are indicated adjacent to each stratigraphic unit

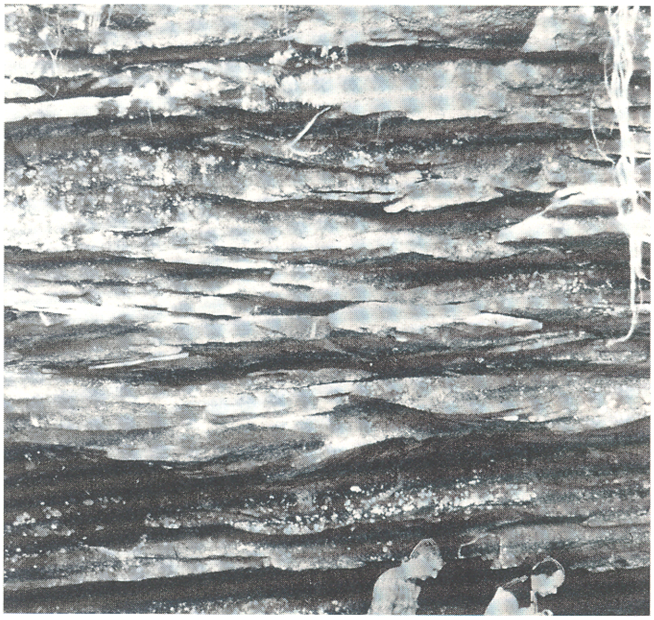


Fig. 5. Outcrop exposure of the upper part of the 'Jagger bedrock' sandstone exhibiting large-scale trough cross-stratification. Bed sets are oriented in a south-eastern to south-western direction towards the inferred coastline. Photograph taken at Mallard Creek, Marion County, Alabama

Jagger – Blue Creek coal interval

An interlaminated sandstone and mudstone facies overlies the Jagger coal and may be up to 10 m thick (3 – 9+ m depending on the geomorphology of the underlying 'Jagger bedrock'). This lithology continues upwards to near the base of the Blue Creek coal. It is characterized by dark to medium grey silty mudstone with light grey, very fine-grained sandstone laminations. The sandstone lamination varies rhythmically from 0.2 to 3 mm in thickness (Fig. 6; Demko et al., 1991). A coarsening upwards trend is noted in this interval, and shallow channel form sandstone bodies with intercalated shale chip conglomerates occur at the top. The tops of these channels may be rooted by stigmarian rhizophores and, locally, erect vegetation may be preserved. Parallel lamination, raindrop imprints and rippled surfaces characterize the suite of primary sedimentary structures. Biogenic structures are restricted to shallow burrows and surface trails (Rindsberg et al., 1990), and are abundant throughout this facies. The pronounced rhythmicity in variation of lamination thickness records diurnal, semi-diurnal, neap – spring and seasonal fluctuations in current strength within a semi-diurnal or mixed tidal system (Demko et al., 1991). The facies is interpreted to represent deposition within tidal flats and associated tidal creeks or channels in the upper reaches of an estuary (Demko and Gastaldo, in preparation).

Blue Creek coal

The Blue Creek coal overlies the root-worked, weakly developed Aqueant soil in the underlying tide-influenced facies (Demko and Gastaldo, 1992). It is the most persistent in the coal zone and can be traced throughout the basin, extending north-westwards into Mississippi (J. C. Pashin, personal communication, 1990). It is thin, varying little in thickness within our study area (0.3 – 0.5 m). Towards the south, in deeper parts of the

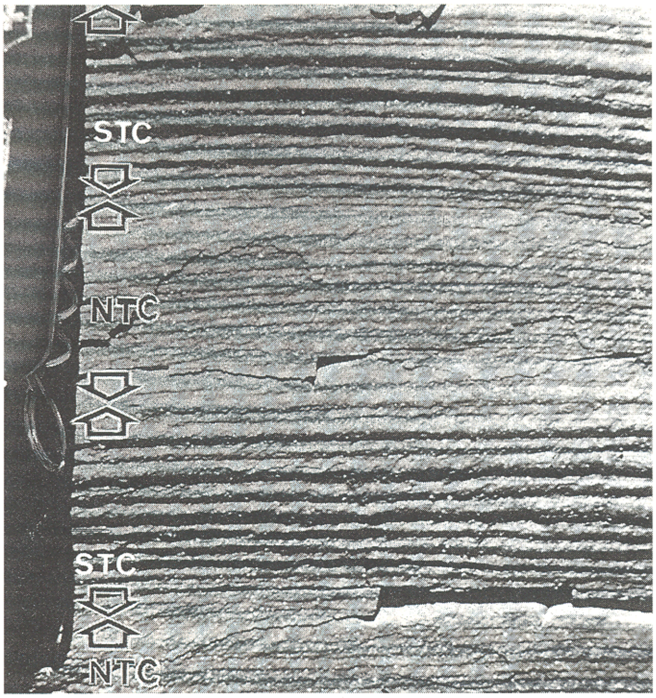


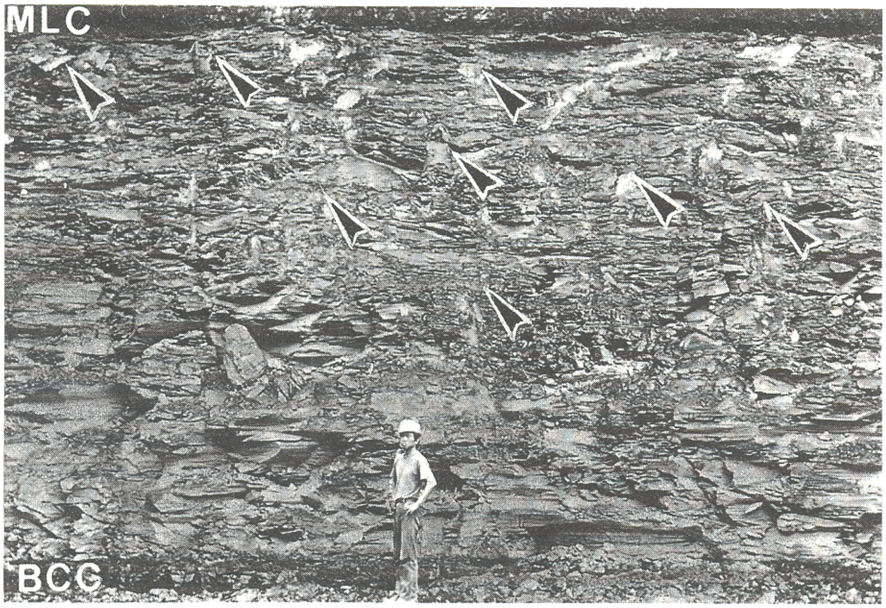
Fig. 6. Rhythmically bundled interlaminated sandstone and mudstone tidalite sequence characteristic of the Jagger – Blue Creek interval. Couplets deposited under neap tidal energies (NTC) alternate with couplets deposited under spring tidal energies (STC) in a mixed tidal system. Photograph taken in the Gateway Malls Hope Galloway Mine, Walker County, Alabama. Knife length in photograph 7.1 cm (photograph × 0.66)

basin and closer to the structural front, the Blue Creek and Mary Lee coals become thicker and may be stratigraphically in very close proximity to each other. The Blue Creek peat forest, one of low systematic diversity, is preserved erect above the coal. Most trees and understory vegetation died as the result of catastrophic stress (Gastaldo et al., 1990). In some instances, however, *Calamites* were capable of regeneration (Gastaldo, 1992). All erect vegetation is preserved either as trunk or pith casts. The peat swamp forest litter is preserved as adpressions within the entombing mudstone directly above the coal as a typical roof shale flora. The Blue Creek coal is interpreted to have accumulated in an autochthonous planar peat mire (Demko and Gastaldo, 1992).

Blue Creek – Mary Lee coal interval

The interval between the Blue Creek and Mary Lee coals is an overall coarsening upwards sequence (Demko and Gastaldo, 1992). It is of variable thickness as a direct result of the palaeotopography of the underlying 'Jagger bedrock' (Demko, 1990). A homogenous mudstone directly overlies the Blue Creek coal, moulding the autochthonous vegetation of the Blue Creek peat mire. These standing trees, however, are not cast by homogenous mudstone, but rather by mudstone and sandstone rhythmites (Gastaldo, 1992). Often these primary structures are homogenized by bioturbation. Mudstone may be intercalated with very fine-grained sandstone lamination and interbeds higher in the interval. Where these occur they are rhythmically bundled, resembling the neap – spring tidalites identified above the Jagger coal and within erect vegetation. Rhythmites are geographically isolated, not as well pronounced, nor as complete as those lower in the section. Thin (>2 m), broad (a few hundred metres) channel form fine-grained sandstone bodies occur locally within palaeotopographic lows inherited from the underlying 'Jagger bedrock'. These either pinch out or grade laterally into interlaminated mudstone and very fine-grained sandstone. There is no evidence of lateral channel migration, and channels appear to have been fixed within the palaeotopographic lows. The characteristic palaeontological feature of this interval is the

Fig. 7. Autochthonous erect fossil forests preserved between the Blue Creek (BCC) and Mary Lee coals (MLC). Erect, mudstone-cast trees are marked by arrows, representing four successive clastic swamps above the Blue Creek coal. Photograph taken in the Drummond Co. Inc. Cedrum Mine, Walker County, Alabama



presence of three to five autochthonous forests, the plants of which were rooted in mineral substrates (Fig. 7; Demko and Gastaldo, 1992). Each forest is preserved by an inundite (*sensu* Seilacher, 1991), the result of burial by catastrophic sedimentation. Vegetation of the uppermost clastic swamp terminates within the base of the overlying Mary Lee coal. This interval is interpreted to represent the continued recolonization of coastal sites following forest burial and death, the result of underlying peat compaction and subsequent inundation by terrestrial sediments (Demko and Gastaldo, 1992).

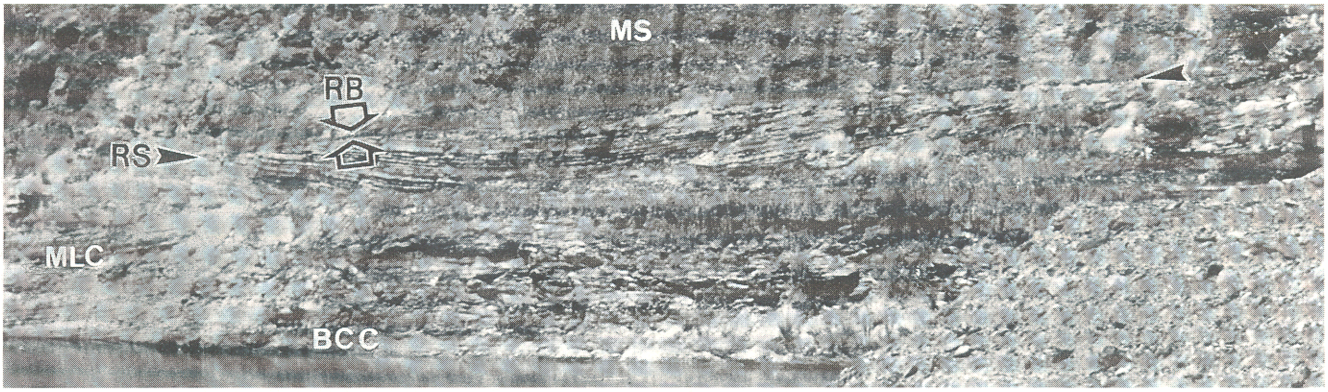
Mary Lee/Newcastle coal

The Mary Lee coal terminates continued clastic swamp regeneration and lies immediately above the uppermost clastic swamp horizon. The coal is widely distributed, can be traced into deeper parts of the basin (Thomas and Womack, 1983), but varies greatly in quality and thickness. For example, in our study area the Mary Lee coal may be composed either of a single seam, two closely spaced benches separated by either a mudstone parting or localized sandstone channel (Liu and Gastaldo, 1992 a), or two locally distinct beds (Mary Lee and Newcastle seams) separated by up to several metres of mudstone and sandstone (Liu, 1990). An erect forest is preserved above each of the coal locations described. The Mary Lee coal, in the broadest sense, is an autochthonous coastal peat mire that was subjected to localized (coal partings resulting in coal benches) and then regional catastrophic burial. Lithologies intercalated within and burying the swamp represent contemporaneous fluvial channel and overbank environments in which there is evidence of increased tidal influence (Gastaldo et al., 1990). Large tidal channels, up to 5 m wide and 4 m deep, have been identified within the interval above the Mary Lee coal seam in the eastern part of the study area (USGS Cordova Quadrangle; Fig. 3).

Ravinement surface and bed

The lithologies above the Mary Lee/Newcastle coal are truncated by an erosional surface that can be traced in outcrop and subsurface for over 1 800 km^2 (Fig. 8; Liu and Gastaldo, 1992 b). It is a disconformable surface separating underlying non-marine from overlying lithologies preserving an offshore marine fauna. The erosional surface is easily distinguished where sandstone overlies mudstone; it is not so easily distinguished on first inspection where mudstone overlies mudstone. A thin bed of sediment immediately overlying the erosional surface provides the key features that allow for the recognition of ravinement (Liu and Gastaldo, 1992 b). The ravinement bed in the western part of the study area is composed of sandstone, with *Zoophycos* bioturbation overlain by a grain-supported bioclast layer containing an allochthonous trilobite–crinoid–brachiopod assemblage. In the eastern part it is composed of mudstone, with an in habitat brachiopod and pelecypod dominant assemblage. The sandstone, typically a massive very fine- to fine-grained, calcite-cemented sublitharenite, is of variable thickness (0.3–0.7 m). Bioclasts are poorly sorted, fragmentary (commonly only single valves comprise up to 50% of the bed), and of open marine systematic affinities (Gibson, 1990). A thin layer of siderite pebble conglomerate is often found to cap this horizon. In contrast, the mudstone is relatively constant in its thickness (0.3 m) without any internal sequencing. Sedimentary structures are obscured by moderate bioturbation and an in habitat concentrated macrofauna. There is no silty lamination as observed in the underlying terrestrial tidally-influenced facies. A thin layer of siderite pebble conglomerate also occurs at the top of this bed. The autochthonous benthic fauna may be locally monospecific or monodominant. The ravinement bed represents a substrate developed by transgressive erosion subsequently colonized by macroinvertebrates when physical conditions were favourable (Liu and Gastaldo, 1992 b).

Fig. 8. Outcrop photograph in the Gateway Malls Hope Galloway, Walker County, Alabama, mine illustrating the field occurrence of the ravinement surface (RS; position indicated by solid arrows). A channel form sandstone body stratigraphically above the Mary Lee coal (MLC) is truncated by the overlying ravinement surface. The ravinement bed (RB; occurring between open arrows) interpreted as a condensed section, overlies this erosional surface. The Morris shale (MS) overlies the ravinement bed



Overlying strata

Overlying the ravinement bed is an interval of grey – black shale within which intercalated siderite concretions or siderite-cemented layers occur. This interval averages 3 m in thickness and is characterized by distinct horizontal bedding. A scattered macrofaunal assemblage, with taxa characteristic of brackish marine conditions, is preserved within the concretions (Gibson, 1990; Gibson and Gastaldo, 1987). The siderite-bearing unit represents cyclical fluctuations in the prevailing geochemical conditions due either to an influx of fresh water or an increase in the organic carbon content under anoxic conditions. It is overlain by a horizontally bedded shale that ranges from a few metres to 30 m in thickness. Scattered macroinvertebrates and trace fossils are preserved within the interval, informally known as the Morris shale (Fig. 8; Raymond et al., 1988). These shales represent deposition in offshore marine conditions. The Gillespie/Curry coal zone (Pashin et al., 1990) occurs stratigraphically above the Morris shale, signalling a return to terrestrial coastal deposition (Fig. 2).

Mary Lee coal zone and relative sea-level changes

Each stratigraphic interval within the Mary Lee coal zone reflects the available accommodation space as circumscribed under a specific set of depositional conditions. These conditions, and the sedimentary facies preserved within this stratigraphic interval, are related to the degree of relative sea-level change operating in this coastal plain environment through time. Therefore, a discussion of each facies in a sea-level context will provide the basis on which to apply sequence and genetic stratigraphic models.

The regionally isolated sandstone body called the 'Jagger bedrock' sits unconformably on underlying marine shale, the characteristics of which resemble the Morris shale (Fig. 4). The basal erosional contact is indicative of a lowering of wave base such that an unknown thickness of fine clastic sediment was removed before the deposition of the sublitharenite. The presence of a thick sandstone overlying the erosional contact demonstrates that the lowering of wave base was not a temporary phenomenon, such as would be found operating during high energy storms within shelf settings. Rather, the change in relative sea level was of longer duration, allowing for the development of interpreted shore-parallel sand bodies. Repetitive, stacked large-scale trough cross-stratification bed sets, with dip directions towards the inferred coastal plain, indicate that marine sedimentation occurred in close proximity to the shore. The internal architecture of bed sets reflects deposition under tidally-influenced conditions (Demko and Gastaldo, in preparation). This feature, in addition to the presence of large dune and sand wave-like megaforms that characterize the top of the sandstone body, indicate that deposition of the sand body occurred under marginal marine conditions. These conditions may have been at water depths shallower than those of the underlying marine lithology. The colonization by lycophytes on the top of, and development of pedogenic structures within, this sandstone unequivocally demonstrate that the top of this sand body was aerially exposed. The stranding of shallow marine sand bodies and their incorporation within subsequently developed coastal plain settings is a common phenomenon of the Quaternary (e.g. Trail Ridge of the Okefenokee Swamp; Pirkle and Pirkle, 1984). We believe that the accretion of this nearshore sand body marks the moment of regional, rather than local, regression. Hence, the 'Jagger bedrock' and other similar sandstone bodies in the Pottsville Formation (e.g. Bremen Sandstone; Haas and Gastaldo, 1986) represent the stranding of nearshore sand bodies onshore.

The development of the Jagger coal directly overlying this sandstone is evidence to suggest a period of sea-level stability, or continued minor base level fluctuation, within the area. Coal thickness is directly correlated with the palaeotopography of the underlying sandstone body (Demko, 1990). It appears that by the time the upper bench of the peat swamp accumulated, conditions for the development of histosols existed throughout this area. This is because the thinner 'upper bench' is found not only within the palaeotopographic lows but also across the palaeotopographic highs. The thicker 'lower bench' is restricted to the base of swales. Forestation on, and accumulation of, a peat substrate requires that a high water-table exists at the site (for a review, see McCabe, 1984). This may be established through high precipitation rates, slight changes in relative base level, or a combination of geomorphological and climatic factors. The preservation of two successive lycophyte forests above the Jagger coal points to the fact that these sites were inundated with terrestrial clastic sediments and recolonization occurred, albeit in a mineral substrate. Lycophytes are generally believed to be indicative of freshwater conditions, although it has been suggested that they could tolerate brackish salinities (Gastaldo, 1986). Therefore it is not possible, on this basis alone, to infer whether or not these forests were tidally influenced. It is also impossible at the present time to determine the parameters responsible for the termination of peat accumulation. Most of the thick Jagger Coal has been mined out, and often what little is left and available for examination in highwalls is poorly exposed. It is certain that the peat swamps were autochthonous, developed under freshwater conditions within a varied coastal plain palaeotopography. It is not certain if peat swamp burial was initiated by catastrophic floods or the incursion of marginal marine settings in response to a change in base level. In either case, the period of time required to accumulate the Jagger peat mire marks an interval of stable (or regressing) sea level.

The Jagger – Blue Creek interval above the standing forests, with the thickest deposits geographically confined to the topographic lows of the underlying sandstone, was deposited unquestionably under a paralic or marginal marine setting. This interlaminated sandstone and mudstone exhibits a pronounced rhythmicity in the variation of lamination thickness similar to that reported in other

Upper Carboniferous tidalites (e.g. Kvale et al., 1989; Kvale and Archer, 1990; Kuecher et al., 1990). Diurnal, semi-diurnal, neap – spring and seasonal fluctuations in current strength are recorded within this mixed tidal system (Demko et al., 1991). The incursion represents a very short-term change in sea level, as reflected by an extremely high depositional rate. The entire tidalite sequence may represent as little as five years of continuous deposition. Depositional rates slowed near the top of the interval with the establishment of tidal channels and subsequent colonization. This short-term phenomenon reflects a very short-term relative sea-level rise within a very specific depositional setting, principally the swales of the underlying 'Jagger bedrock'. Presently, we are not able to interpret it specifically as a function of eustatics, localized compaction of underlying sediment (particularly the Jagger peat; Gastaldo et al., 1991), or regional subsidence related to tectonism. As the interlude of time represented within the Jagger – Blue Creek interval is geologically instantaneous, up to 10 m of sediment deposited in approximately five years, we tend to discount eustatics as the agent responsible for relative sea-level change. It would be difficult to account for the abrupt volume of generated accommodation space by eustatic rise. Sediment accumulation rates are high in areas affected by short-term tectonic changes in base level (Klein and Kupperman, 1992). Short-term, nearly complete sedimentological records, such as that found in the Jagger – Blue Creek interval, may directly reflect tectonically induced base-level changes.

The Blue Creek coal, being the most persistent and widespread coal in this coal zone (J. C. Pashin, personal communication, 1990), represents a period of time when the coastline was far to the north-west of our study area. Its palynological and coal palaeobotanical characteristics and relative thinness are evidence for a planar or immature 'domed' geomorphology (Demko and Gastaldo, 1992; Eble et al., in press). Mire development was terminated by burial of suspension load mud during a catastrophic flooding event. This resulted in the regional compaction of the peat mire and subsidence to near base level. Although there is no evidence for marginal marine sedimentation in the lithologies directly overlying the flood deposit, tidally-driven short-term inundation did occur. Pith casts of erect vegetation preserve evidence of tidalite deposition and subsequent bioturbation (Gastaldo, 1992). This reflects a change in local conditions without the development of significant accommodation space. Continued sediment loading occurred via high energy low frequency floods. This resulted in compaction of the underlying peat within the area and the development of successive clastic swamp forests (Gastaldo et al., 1991). Localized microtopographic differences throughout the area led to the irregularly distributed occurrences of laminated sandstone and mudstone interbeds and very fine-grained sandstone. Once stabilization of the coastal plain sediments occurred, peat accumulation was reinitiated (Mary Lee coal). In effect, the sea level remained virtually stationary during the time required to deposit the Blue Creek to Mary Lee interval – that is, subsidence rates were equaled by sedimentation rates.

The presence of an admixture of fully tidal and tidally-influenced fluvial environments within and above the Mary Lee coal (inclusive of the Newcastle coal) signals a change in sedimentation style within our study area. Pronounced tidalites that mould and cast erect trees above the coal manifest the difference between the preservation of these trees and those found in the underlying Blue Creek – Mary Lee interval. Where sediment loading punctuated peat accumulation in the Blue Creek – Mary Lee interval, evidence for tidal incursion was restricted to within tree casts. There was no additional accommodation space developed that allowed for widespread and thick tidalite accumulation. Hence there was effectively no significant rise in relative sea level. Compaction of the underlying Blue Creek coal lowered the land surface to near base level, thereby allowing tidal inundation (Demko and Gastaldo, 1992; Gastaldo, 1992). Although sediment loading of peat substrates also occurs in the Mary Lee coal, there appears to be an accompanying notable change in the relative position of sea level. Only such a relative rise in sea level could account for the development of the accomodation space in which tidalite deposition is found to be widespread, accreted around erect trees. If relative sea-level rise did not occur contemporaneously, imperfect and scattered tidalite deposition would be found similar to those in the Blue Creek – Mary Lee interval. In addition, the presence of tidally-influenced channels in the western part of the study area and large tidal channels above the Newcastle coal in the eastern part of the study area point to a relative sea-level change of an order of magnitude similar to that responsible for the Jagger – Blue Creek interval.

Confirmation of sea-level rise is reflected in the erosional planation of these tidally-influenced channels and the development of a ravinement surface (Liu and Gastaldo, 1992b). The ravinement surface can be traced over an area of approximately 1 800 km^2 and along a transgressive track of more than 60 km. Shoreface retreat of the order of kilometres is considered to be a response to longer term sea-level rise (Everts, 1987).

The lithologies that comprise the ravinement bed result from the offshore deposition of the material eroded during shoreface retreat (Larue and Martinez, 1989). Therefore, the distribution of facies within the ravinement bed across the study area reflects the composition of those sediments transgressed (Liu and Gastaldo, 1992b). These lithologies alone provide little information about the water depth and distance from shoreline under which they resided. Therefore, palaeontological evidence must be used to provide some constraints on relative sea-level depth. Substrate conditions, water turbidity and salinities are but a few principle factors affecting macroinvertebrate colonization of shelf environments (Tasch, 1973). The in habitat macrofauna (a primary biogenic concentration) of the ravinement bed is composed of fully marine filter-feeding brachiopods and bivalves, the taxonomic diversity of which is variable with locality (Gibson, 1990). Both articulated juveniles and adults coexist in these assemblages, indicating that an established regenerative community existed in the substrate. These organisms require non-turbulent waters, normal salinities and relatively stable substrates. In effect, the waters in these offshore sites must be relatively free of suspended fine-grained clastics, some distance away from the influence of freshwater pulses, and in a location where depositional rates are low. These conditions are essential for the survival of these organisms. Such a situation only exists in a geographical position distal to the shoreline, kilometres away from the debouchment of sediment plume(s) and several tens of metres below wave base. Dissolved and fine-particulate organics, originating from an eroding shoreface, may be transported into this site providing a food source for macroinvertebrates (Liu and Gastaldo, 1992b). It is believed that this assemblage represents stable open ocean conditions.

Additional data exist to support our interpretation that the ravinement bed represents an offshore shelf environment. Conditions in this area where the ravinement bed is composed of sandstone were stable for some period of time. This is illustrated by the presence of well developed biogenic structures (principally *Zoophycos* traces) within the basal horizon. Overlying this zone of bioturbation is an allochthonous (transported) macroinvertebrate assemblage preserved in a calcite-cemented sublitharenite. This sandstone may be composed of up to 50% bioclasts, consisting of crinoids, trilobites, brachiopods and molluscs. These poorly sorted fossils are either fragmentary or isolated parts. Systematically and ecologically they represent a community quite different from the in habitat community preserved in the mudstone facies. We interpret this secondary biogenic concentration (tempestite concentration) as resulting from a lowering of wave base during a severe storm event, and transport of the bioclasts to the depositional site. We do not believe that the accumulation represents a transgressive lag deposit. The palaeontological composition of the concentration reflects components derived from offshore marine communities, rather than a reworking of nearshore taxa. The presence of a single secondary biogenic concentration lends credence to deeper offshore water depths during the time of infaunal colonization. If this site was within a short distance from shore, its sedimentary character would reflect deposition and disruption from frequent storms or storm surges, or both.

The development of siderite concretions and siderite-cemented beds in the Morris shale above the ravinement bed signals a cyclical change in geochemical conditions. The formation of siderite concretions occurs in response to methanogenesis either in freshwater or marine environments (Curtis et al., 1972; Gautier, 1982). We do not have geochemical data, at the present time, to determine whether or not marine or freshwater conditions prevailed. It is possible that freshwater inundation may have been responsible for an increase in organic carbon that underwent methanogenesis, resulting in concretion development. This alternative is favoured by palaeontological evidence. There is a dramatic reduction in the systematic diversity of macroinvertebrates preserved within the concretionary horizons. Orbiculoid brachiopods predominate this assemblage. These are epiphytic taxa that live under brackish and/or fluctuating salinities (M. Gibson, personal communication, 1992). The remainder of the Morris shale also preserves a low diversity but widely scattered macroinvertebrate population. No widespread in habitat macroinvertebrate assemblages have been identified in this unit. Rather, the individuals that are preserved are extremely small, representing either juveniles or stunted forms (Pody and Dewey, 1986). These features taken as a whole are indicative of organism stress. Such stress may be initiated by increasing turbidity, higher sedimentation rates, and/or increasing freshwater discharge resulting in salinity fluctuations.

The Morris shale is a shallowing-up sequence overlain by a sandstone body of unknown characteristics and geometry. It is interpreted as having been deposited in nearshore environments where macroinvertebrates were subjected to increasingly stressful physical conditions. This unit therefore represents an interval of time when the input of terrestrial clastic sediments increased. We believe that this reflects shoreline progradation. Progradation is either accompanied, or followed, by relative sea-level lowering and colonization by terrestrial vegetation in subaerially exposed environments. Palaeosols in the lowermost Gillespie/Curry coal zone indicate such a sequence.

Applicability of genetic and sequence stratigraphy

Our ability to recognize the existence of a transgressive erosional surface and fluctuations in relative sea level as recorded in sediments within the Mary Lee coal zone provide the basis on which to apply sequence and genetic stratigraphic models to the Carboniferous of the Black Warrior basin. The ravinement surface (or marine flooding surface, Galloway, 1989; flooding surface of Van Wagoner et al., 1990) represents the erosion of underlying terrestrial deposits resulting from a rapid rise in sea level and shoreface transgression landwards. Sequences in these contrasting models are defined on different bounding surfaces. Flooding surfaces mark the upper bounding surface of a parasequence and the lower boundary of the overlying parasequence in sequence stratigraphic terminology (Van Wagoner et al., 1990). The top of the condensed section (maximum flooding surface) marks the upper bounding surface of a genetic stratigraphic sequence (Galloway, 1989). Therefore, each hypothesis will be discussed separately with regard to how we believe the Mary Lee coal zone conforms to these models.

Genetic stratigraphy

According to Galloway (1989), bounding hiatal surfaces separate stratigraphic packages that reflect significant interruptions in basin depositional history. Although several types of unconformities are acknowledged, the bounding hiatal surfaces chosen as the upper and lower boundaries of a genetic stratigraphic sequence (GSS) are both maximum flooding surfaces (MaxFS). Its transgressive character and the dramatic change that is reflected in a major basinal reorganization with regard to palaeographical framework constrain genetically related rock intervals. Offlap (or regressive) and onlap (or transgressive) components are identified within the GSS.

The top of the ravinement bed (the bed is considered to be the equivalent of a condensed section) identified by Liu and Gastaldo (1992b) marks a GSS upper bounding surface; the lower bounding surface is below the 'Jagger bedrock' sandstone. The interval between the Ream coal and the 'Jagger bedrock' is poorly exposed. However, critical stratigraphic relations were discerned using continuous cores and several isolated outcrops (Fig. 3). Demko (1990) has identified in core a ravinement surface and transgressive lag situated above the Ream coal seam throughout the area (Table 1). The ravinement surface may directly overlie the lower bench of the Ream coal. A marine condensed section overlies the ravinement surface, the upper horizon of which is burrowed (Demko, 1990). Infaunal colonization is indicative of a period of sediment starvation in the area. This horizon is interpreted to represent the MaxFS and, hence, deepest water conditions. Hence it is our contention that the Ream coal is not part of the Mary Lee coal zone as delimited by numerous workers over the past century (e.g. Butts, 1926; Raymond et al., 1988). It marks the upper part of the underlying GSS; the lower limits of the Ream coal zone have not been identified to date.

The strata comprising the Mary Lee coal zone can be positioned within an idealized GSS, following the delimitation of the upper and lower bounding surfaces (Fig. 9). The condensed section overlying the basal ravinement surface is part of the onlap component, representing reworked shore zone and shelf facies during shoreline advancement landward (Liu and Gastaldo, 1992b). We are unable to determine, due to limited data, if the onlap component may have been much thicker in our study area. The unconformable base of the overlying 'Jagger bedrock' sandstone, the first unequivocal offlap component, marks an erosional diastem in the stratigraphic record.

Table 1. Location of ravinement surface above the Ream coal seam in KRCRA cores. See Fig. 3 for location of cores in study area

KRCRA Core No.	Depth of ravinement surface (m)	Description
15	188.7	Siderite pebble conglomerate in sandstone matrix
16	210.2	Bioturbated sandy mudstone with fusian fragments
17	120.4	Siderite pebble conglomerate
18	152.4	Eroded; base of Jagger Bedrock sandstone
20	144.6	Eroded; base of Jagger Bedrock sandstone
21	117.2	Eroded; base of Jagger Bedrock sandstone
22	40.9	Siderite/shale chip conglomerate; burrowed

* See Fig. 3 for core location

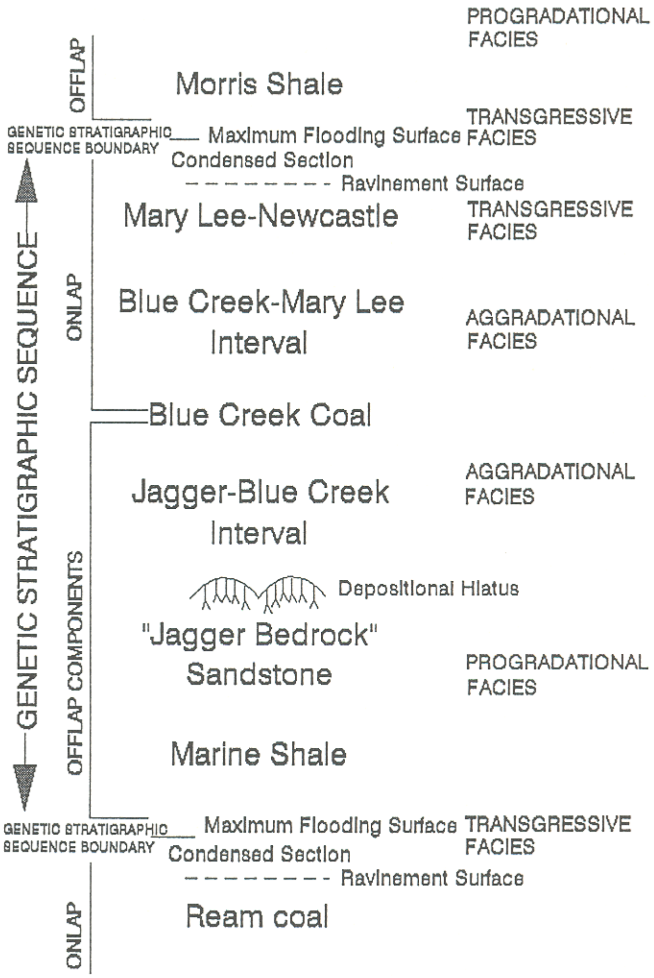


Fig. 9. Mary Lee coal zone as interpreted within the constraints of genetic stratigraphy

In addition to the 'Jagger bedrock' sandstone (representative of a tidally-influenced sandy shore zone subsequently stranded), other offlap components include the Jagger coal – Blue Creek interval (Fig. 9). The Jagger coal – Blue Creek interval represents an interplay between coastal plain aggradation and estuarine (bay/lagoon) conditions. Short-term relative changes in sea level reflected in the tidalite sequence are not considered significant deviations from the long-term regressive phase. The subsequent interval of alternating peat mires and clastic swamps of the Blue Creek to Newcastle coals can be considered to be interdeltaic (coastal plain) aggradational facies formed on the progradational foundation of the underlying strand plain deposits ('Jagger bedrock'). This foundation affects the distribution and thickness of all coals in the western part of the study area where the sandstone body exists (Demko and Gastaldo, 1992).

The reappearance of tidalites and tidally-influenced channels within and above the Mary Lee coal (inclusive of the Newcastle coal seam) mark transgressive influence in the area. It is not possible to determine exactly what these onlap features may represent. According to the hypothesis, these would indicate the reworking of shore zone and shelf facies into sites where greater accommodation space was generated. An alternative explanation would favour an increased longshore drift component in the depositional system transporting fluvially-derived sediment to these sites. This would result as shoreline processes moved landwards. It is certain that the onlap component is fully manifested in the development of the ravinement surface that truncates the terrestrial and nearshore deposits. A ravinement bed of variable lithological and palaeontological characteristics overlies the transgressive erosional surface, and we interpret this as the equivalent of the condensed section (Liu and Gastaldo, 1992b). The top surface of this bed is considered to be the MaFS and, therefore, the upper bounding surface of the GSS.

Galloway (1989) states that active sedimentation is a common phenomenon during transgression. Such activity may result in thick marine deposits in response to landward-stepping depositional events. Liu and Gastaldo (1992b) have used this argument to explain the ravinement bed and basal part of the overlying Morris shale. It is also possible that the siderite nodule-bearing basal part of the Morris shale represents the progradational facies of the following offlap component. Several lines of evidence may be used to support this latter interpretation. First, the decrease in macrofaunal diversity, coupled with a decrease in the abundance and size of individuals, throughout the Morris shale interval points to an increase in environmentally stressful conditions under which invertebrates had to live. The thick marine sequence itself signals an increase in sediment load and, hence, turbidity. The cyclical alternation of siderite-rich nodular horizons may be indicative of increased pulses of freshwater discharge into the shelf environs, rather than changes in pore water anoxia. Geochemical data are not yet available to settle the question about the causes responsible for siderite genesis.

Sequence stratigraphy

According to proponents of sequence stratigraphy (for a detailed elaboration in siliciclastic strata see Van Wagoner et al., 1990), marine flooding surfaces (MFS) and their correlative surfaces in coastal plain and basinal settings mark parasequence boundaries. In the former, this is where an abrupt increase in water depth was rapid enough to overcome deposition. When the rate of deposition exceeds the rate of water depth increase, then a new parasequence develops. Parasequence boundaries constrain genetically-related facies assemblages, and relatively conformable successions of unconformity-bounded genetically-related strata are grouped into sequences. Sequences are subdivided into systems tracts that reflect contemporaneous depositional systems.

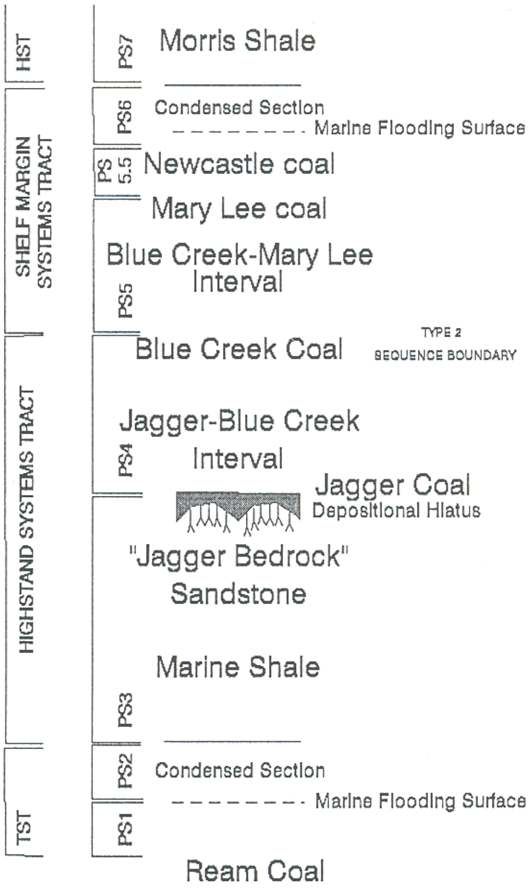


Fig. 10. Mary Lee coal zone as interpreted within the framework of sequence stratigraphy. Parasequences (PS) are identified within transgressive (TST), highstand (HST), or shelf margin systems tracts

The first parasequence set that we recognize includes the rock above the top of the Ream coal to the identified ravinement surface (Fig. 10, PS1). This erosional surface, the equivalent of the MFS, separates younger strata from older strata with an accompanying increase in water depth. The ravinement surface is overlain by a transgressive lag. This lag is interpreted as a condensed section. Bioturbation at the top of this bed reflects an extended interval of time that allowed for colonization. The interval between the ravinement surface and the top of the condensed section is interpreted as a second parasequence (PS2).

It is difficult to apply the criteria established for parasequence recognition in terrestrial coastal settings. We believe that four parasequences can be delimited above the condensed section. The first of these, parasequence 3 (PS3), is composed of the upwards shoaling of offshore and nearshore facies under progressively shallower water. It is an upwards coarsening sequence capped by the 'Jagger bedrock' sandstone. This sandstone body overlies the marine mudstone lithology that is preserved sporadically, due to an erosional diastem, above the condensed section. A non-depositional diastem occurs at the top of the 'Jagger bedrock' and is evidenced by its transformation to a weakly developed palaeosol. Following colonization in a sand substrate, histosols

Final remarks

Of the two models which have been proposed for a shoreline path at the Pleistocene – Holocene boundary the latter is more reliable as it is supported by more data. It is also the only one which can explain the changes in the economy of the Mesolithic people and the occurrence of freshwater fish in that period. The origin of the so-called marine terraces detectable on the flysch subbottom has not yet been clearly explained.

If the U-Th calibration (Bard et al., 1990) is reliable in this area (and this must be proved) and we correct the dates following it, whichever model we consider can work correctly only if we infer very strong tectonic activity. This is also suggested by hints of older tectonics that may have lasted for a long time. Thus we can finally conclude that the Karst region has undergone a rise in the Quaternary era, probably in the second half; this continued in the Late Pleistocene, probably until its end.

This work must not be considered as a definitive reconstruction of the Quaternary history of sea-level changes and neotectonics in the northern Adriatic. The principal aim has been to try to integrate all the available data and infer some models from them. It is also evident that more specific work must be carried out on this subject.

References

Albrecht P, Mosetti F (1987) Karst evolution and sea-level. Mem Soc Geol Ital 40: 383 – 387

Ambrosetti P, Bartolomei G, Ficcarelli G, Torre D (1979) La breccia ossifera di Slivia (Aurisina-Sistiana) nel Carso di Trieste. Boll Soc Paleontol Ital 18: 207 – 220

Andreolotti S (1965) Rinvenimento di un deposito alluvionale ciottoloso-argilloso in una cavità relitto del Carso di Basovizza. Atti e Mem Comm Grotte 'E Boegan' 4: 21 – 26

Bard EE, Hamelin B, Fairbanks RG, Zindler A (1990) Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados Corals. Nature 345: 405 – 410

Belloni S, Orombelli G (1972) I depositi fluviali di riempimento di alcune cavità carsiche nei dintorni di Trieste. Riv Ital Paleontol 78: 163 – 172

Benussi B, Melato M (1968) Considerazioni su alcuni ritrovamenti in brecce pleistoceniche del Carso. Atti e Mem Comm Grotte 'E Boegan' 8: 3 – 20

Benussi B, Melato M (1969) Considerazioni preliminari sui reperti di una fauna fossile a Pachidermi in una breccia ossifera a Slivia-Visogliano. Atti e Mem Comm Grotte 'E Boegan' 9: 20 – 28

Boschian G (1991) Un nuovo dato di cronologia assoluta nel quadro culturale del Mesolitico e del Neolitico del Carso triestino. Atti Civici Mus St ed A 15 (1985 – 1987): 49 – 56

Boschian G, Montagnari-Kokelj E (1984) Siti mesolitici del Carso triestino: dati preliminari di analisi del territorio. Atti Conv Int 'Preistoria del *Caput Adriae*', Trieste, 19 – 20 Novembre 1983. Ist Encicl Friuli-V Giulia, Trieste: 40 – 50

Boschian G, Pitti C (1984) I livelli mesolitici della Grotta dell'Edera. Atti Soc Preist Protost Friuli-V Giulia Qd. 5: 143 – 210

Broglio A (1980) Culture e ambienti della fine del Paleolitico e del Mesolitico nell'Italia nordorientale. Preistoria Alpina 16: 7 – 29

Carobene L, Carulli GB (1981) Foglio 40/a Gorizia e 53/a Trieste. In: Castellarin A (ed) Carta Tettonica delle Alpi Meridionali (alla scala 1 : 200 000) Rome: 8 – 13

Carulli GB, Cucchi F (1991) Proposta di interpretazione strutturale del Carso Triestino. Atti Ticin Sc Terra 34 (1991): 161 – 166

Carulli GB, Carobene L, Cavallin A, Martinis B, Onofri R (1980) Evoluzione strutturale Plio-Quaternaria del Friuli e della Venezia Giulia. Contrib Prelim Realizz Carta Neotett d'Italia. Pubbl n° 356 PF Geodinamica. Napoli: 489 – 545

Cremonesi G (1978 – 81) Caratteristiche economico-industriali del Mesolitico nel Carso. Atti Soc Preist Protost Friuli-V Giulia IV: 171 – 186

Cremonesi G, Radmilli AM, Tozzi C (1973) A proposito del Mesolitico in Italia. Atti Soc Tosc Sc Nat LXXX: 106 – 120

Cremonesi G, Meluzzi C, Pitti C, Wilkens B (1984) Grotta Azzura: scavi 1982 (Nota preliminare). Atti Soc Preist Protost Friuli-V Giulia Qd. 5: 21 – 64

Cremonesi G, Pitti C, Radmilli AM (1984) Considerazioni sul Mesolitico del Carso triestino. Atti Soc Preist Protost Friuli-V Giulia Qd. 5: 229 – 240

Cucchi F, Pirini Radrizzani C, Pugliese N (1987) The Carbonate Stratigraphic Sequence of the Karst of Trieste (Italy). Mem Soc Geol Ital XL-1989: 35 – 44

Cucchi F, Pugliese N, Ulcigrai F (1989) Il Carso triestino: note geologiche e stratigrafiche. Int J Speleol 18: 49 – 64

d'Ambrosi C (1955) Note illustrative alla carta geologica delle Tre Venezie. Foglio 'Trieste' Uff Idrogr Mag Acque: 1 – 85

d'Ambrosi C (1956) Studio geologico sulla stabilità e consistenza dei terreni lungo la costra tra Trieste e Monfalcone con riferimento al tracciato in progetto per il futuro acquedotto di Trieste. Boll Soc Adr Sc Nat 48: 9 – 24

Finetti I (1967) Ricerche sismiche a rifrazione sui rapporti strutturali fra il Carso ed il Golfo di Trieste. Boll Geof Teor ed Appl IX, 35: 17 – 22

Finetti I (1984) Struttura ed evoluzione della microplacca adriatica. Boll Soc Adr Sc 51: 39 – 58

Giorgetti F, Mosetti F, Macchi G (1968) Caratteristiche morfologiche, fisiche e chimiche del fondo marino del Golfo di Trieste nell'area compresa entro la congiungente Punta Grossa-Bocche di Primero. Boll Soc Adr Sc LVI, 1: 3 – 21

Marocco R (1989) Evoluzione quaternaria della Laguna di Marano (Friuli-Venezia Giulia). Il Quaternario, 2, n° 2: 125 – 137

Martinis B (1987) The Development of Geological Information on the 'Carso'. Mem Soc Geol Ital XL-1989: 21 – 34

Marussi A (1941) Il Paleotimavo e l'antica idrografia subaerea del Carso triestino. Boll Soc Adr Sc XXXVIII: 13 – 40

Marussi A (1966) Correlazione tra carsismo epigeo ed ipogeo. In: Desio A (ed) Convegno sul Problema delle Acque in Italia: 153 – 160

Morelli C, Mosetti F (1968) Rilievo sismico continuo nel Golfo di Trieste. Andamento della formazione arenacea (flysch) sotto il fondo marino nella zona tra Trieste, Monfalcone e Grado. Boll Soc Adr Sc LVI, 1: 42 – 57

Pirazzoli PA (1991) World Atlas of Holocene Sea-level Changes. Elsevier, Amsterdam: 300 pp.

Placer L (1981) Geologic Structure of S. W. Slovenia. Geologija 24/1: 27 – 60

Sala B (1977) L'ippopotamo nel pleistocene superiore in italia. Considerazioni paleoecologiche. Riv. sc. preist. XXXII (1 – 2), 283 – 286

Stache G (1889) Die Liburnische Stufe und deren Grenz-Horizonte. Eine Studie über die Schichtenfolgen der cretacisch-eocänen oder protocänen Landbildungsperiode im Bereiche der Küstenlander von Österreich-Ungarn. Abhl K K Reichanst 113: 1 – 170

von Morlot A (1848) Über die Geologischen Verhältnisse von Istrien. Haidingers Naturwiss Abh B. II, T. II: 257 – 318

castle coals), the tidally-influenced interval beginning above the Mary Lee coal, and the terrestrial Blue Creek to Mary Lee coal interval. Offlap components include the basal marine shale overlain by the nearshore 'Jagger bedrock' sandstone, the tidally-influenced Jagger to Blue Creek coal interval. There is a distinct asymmetry in the distribution of onlap and offlap components within the Mary Lee coal zone, with most of the strata representing offlap components.

Transgressive, highstand and shelf margin systems tracts have been identified within the sequence stratigraphy framework. The transgressive systems tract occurs above the Ream coal, with a condensed section overlying the marine flooding surface. A highstand systems tract is comprised of two parasequences. The first includes the marine offshore (shale above the condensed section) and nearshore lithologies ('Jagger bedrock' sandstone), whereas the second encompasses the Jagger to Blue Creek coal interval. The Blue Creek coal, the most geographically extensive coal in the coal zone, is considered to be the terrestrial equivalent of a marine condensed section. It is considered to be a type 2 boundary. Our justification for this boundary assignment is as follows. The concept of a marine condensed section is generally thought of as the site of maximum sediment starvation in the basin associated with shoreline advancement landwards. When the shoreline progrades into the basin, however, theoretically there will be a point in the basin that is also sediment-starved for a period of time. The position of the condensed section shifts within the basin corresponding to the shift in shoreline. With this in mind, at the same time as the marine condensed section is developing, there is a 'condensation' of time in the coastal plain setting. The terrestrial equivalent of this 'time-averaged' section is a soil. In this instance, we equate the Blue Creek coal, the most widely distributed Aqueant in the terrestrial section, with the marine condensed section, therefore a type 2 boundary.

The overlying shelf margin systems tract consists of the stacked clastic swamps of the Blue Creek – Mary Lee interval, the tidally-influenced Mary Lee/Newcastle coal, and lithologies above the Newcastle coal. The shelf margin systems tract is terminated by the presence of an overlying ravinement surface. This ravinement surface is the boundary between the shelf margin systems tract and the condensed section that overlies the surface. The Morris shale is placed in the next highstand systems tract that ends somewhere in the base of the stratigraphically successive Gillespie/Curry coal zone.

Recent investigations have shown that concurrent extrinsic mechanisms controlled cyclicity in Carboniferous strata. Tectonics, particularly in foreland basins such as the Black Warrior basin, play a significant part in short-term base-level changes. Sequence and genetic stratigraphy are both applicable in these Carboniferous strata. The Black Warrior basin is only now being evaluated using basin analysis techniques. It is difficult for us, at present, to predict which of the two techniques may ultimately be most applicable in this foreland basin. Identification of parasequences and marine flooding surfaces, and the ease of identification and local correlation, make these more pragmatically applicable to field and core investigations. Because of these factors, we favour the use of the sequence stratigraphy paradigm as the basis for futher studies within this basin.

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References

Bergman KM, Walker RG (1987) The importance of sea-level fluctuations in the formation of linear conglomerate bodies, Carrot Creek Member of Cardium Formation, Cretaceous western interior seaway, Alberta, Canada. J Sedim Petrol 57: 651 – 665

Butts C (1926) Paleozoic rocks. In: Adams GI, Butts C, Stephenson LW, Cooke W (eds) Geology of Alabama. Geol Surv Alabama Spec Rep No 14: 41 – 230

Cecil CB (1990) Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks. Geology 18: 533 – 536

Cross T (1989) Controls on coal distribution in transgressive-regressive cycles, Upper Cretaceous, western Interior, U.S.A. In: Wilgus CK, Hastings BS, Kendall CGStC, Posamentier HW, Ross CA, Van Wagoner JC (eds) Sea-level Changes: an Integrated Approach. Spec Publ Soc Econ Paleontol Mineral No 42: 371 – 380

Curtis CD, Petrowski C, Oertel G (1972) Stable carbon isotope ratios within carbonate concretions: a clue to place and time of formation. Nature 235: 98 – 100

Demko TM (1990) Depositional environments of the lower Mary Lee coal zone, Lower Pennsylvanian "Pottsville" Formation, northwestern Alabama. In: Gastaldo RA, Demko TM, Liu Y (eds) Carboniferous Coastal Environments and Paleocommunities of the Mary Lee Coal Zone, Marion and Walker Counties, Alabama. Geological Survey of Alabama, Tuscaloosa: 5 – 20

Demko TM, Gastaldo RA (1992) Paludal environments of the Mary Lee coal zone, Pottsville formation, Alabama: stacked clastic swamps and peat mires. Int J Coal Geol 20: 23 – 47

Demko TM, Gastaldo RA. Tide-influenced depositional environments in the Upper Pottsville Formation, Warrior Basin, Alabama: nearshore sand bodies and inshore tidal flats, in preparation

Demko TM, Jirikowic J, Gastaldo RA (1991) Tidal cyclicity in the Pottsville Formation, Warrior basin, Alabama: sedimentology and time-series analysis of a rhythmically laminated sandstone-mudstone interval. Geol Soc Am Abstr Progr 23 (5): A287

Eble CF, Gastaldo RA, Demko TM, Liu Y. in press Coal compositional changes along an inferred swamp margin to swamp interior transect in the Mary Lee coal bed, Warrior basin, Alabama, U.S.A., Int J Coal Geol

Everts CH (1987) Continental shelf evolution in response to a rise in sea level. In: Nummedal D, Pilkey OH, Howard JD (eds) Sea-level Fluctuation and Coastal Evolution. Spec Publ Soc Econ Paleontol Mineral No 41: 223 – 239

Ferm JC, Ehrlich RL (1967) Petrology and stratigraphy of the Alabama coals. In: Ferm JC, Ehrlich RL, Neathery T (eds) A Field Guide to Carboniferous Detrital Rocks in Northern Alabama. Geol Soc Am Coal Division, 1967 Field Trip: 11 – 15

Galloway WE (1989) Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. Am Assoc Petrol Geol Bull 73: 125–142

Gastaldo RA (1986) Implications on the paleoecology of autochthonous Carboniferous lycopods in clastic sedimentary environments. Palaeogeogr Palaeoclimatol Palaeoecol 53: 191–212

Gastaldo RA (1992) Regenerative growth in fossil horsetails following burial by alluvium. Histor Biol 6: 203–220

Gastaldo RA, Demko TM, Liu Y (1990) Carboniferous Coastal Environments and Paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama. Geological Survey of Alabama, Tuscaloosa: 124 pp

Gastaldo RA, Demko TM, Liu Y (1991) A mechanism to explain persistent alternation of clastic and peat-accumulating swamps in Carboniferous sequences. Bull Soc Geol Fr 162: 155–161

Gautier DL (1982) Siderite concretions as indicators of early diagenesis in the Gammon Shale (Cretaceous). J Sedim Petrol 52: 859–871

Gibson MA (1990) Common macroinvertebrates associated with the Mary Lee coal zone (Pennsylvanian, Upper Pottsville Formation, northern Alabama). In: Gastaldo RA, Demko TM, Liu Y (eds) Carboniferous Coastal Environments and Paleocommunities of the Mary Lee Coal Zone, Marion and Walker Counties, Alabama. Geological Survey of Alabama, Tuscaloosa: 97–104

Gibson MA, Gastaldo RA (1987) Invertebrate paleoecology of the Upper Cliff Coal Interval (Pennsylvanian), Plateau Coal Field, northern Alabama. J Paleontol 61: 339–350

Gillespie WH, Rheams LA (1985) Plant megafossils from the Carboniferous of Alabama, U.S.A. In: Escobeda JL, Granádos LF, Melndez B, Pignatelli R, Ray R, Wagner RH (eds) Diéxime Congrés International de Stratigraphie et de Géologie du Carbonifere. Vol. 2: 191–202

Haas C, Gastaldo RA (1986) Flood tidal deltas and related back-barrier systems: Bremen Sandstone, "Pottsville" Formation, Black Warrior Basin, Alabama. Geol Soc Am Centennial Field Guide-Southeastern Section No 40: 181–183

Hewitt JL (1984) Geologic overview, coal, and coalbed methane resources of the Warrior Basin – Alabama and Mississippi. In: Rightmire CT, Eddy GE, Kirr JN (eds) Coalbed Methane Resources of the United States. Am Assoc Petrol Geol Stud Geol Ser No 17: 73–104

Joeckel RM (1989) Geomorphology of a Pennsylvanian land surface: pedogenesis in the Rock Lake Shale Member, southeastern Nebraska. J Sedim Petrol 59: 469–481

Kidd JT (1982) Structural geology of the Black Warrior basin in Alabama. In: Benson J, Rheams LA (eds) Depositional Setting of the Pottsville Formation in the Black Warrior Basin. 19th Field Trip Guidebook of the Alabama Geological Society: 27–34

Klein G de V (1990) Pennsylvanian time scales and cycle periods. Geology 18: 455–457

Klein G de V, Kupperman JB (1992) Pennsylvanian cyclothems: methods of distinguishing tectonically induced changes in sea level from climatically induced changes. Geol Soc Am Bull 104: 166–175

Klein G de V, Willard DA (1989) The origin of the Pennsylvanian coal-bearing cyclothems of North America. Geology 17: 152–155

Kuecher GJ, Woodland BG, Broadhurst FM (1990) Evidence of deposition from individual tides and of tidal cycles from the Francis Creek Shale (host rock to the Mazon Creek Biota), Westphalian D (Pennsylvanian), northeastern Illinois. Sedim Geol 68: 211–221

Kvale EP, Archer AW (1990) Tidal deposits associated with low-sulfur coals, Brazil Formation (Lower Pennsylvanian), Indiana. J Sedim Petrol 60: 563–574

Kvale EP, Archer AW, Johnson HR (1989) Daily, monthly, and yearly tidal cycles within laminated siltstones (Mansfield Formation: Pennsylvanian) of Indiana. Geology 17: 365–368

Larue DK, Martinez PA (1989) Use of bed-form climb models to analyze geometry and preservation potential of clastic facies and erosional surfaces. Am Assoc Petrol Geol Bull 73: 40–53

Liu Y (1990) Depositional environments of the upper Mary Lee coal zone, Lower Pennsylvanian "Pottsville" Formation, northwestern Alabama. In: Gastaldo RA, Demko TM, Liu Y (eds) Carboniferous Coastal Environments and Paleocommunities of the Mary Lee Coal Zone, Marion and Walker Counties, Alabama. Geological Survey of Alabama, Tuscaloosa: 21–39

Liu Y, Gastaldo RA (1992a) Characteristics and provenance of log-transported gravels in a Carboniferous channel deposit. J Sedim Petrol, 62: 1072–1083

Liu Y, Gastaldo RA (1992b) Characteristics of a Pennsylvanian ravinement surface. Sedim Geol 77: 197–214

Lyons PC, Meissener CR, Jr, Barwood HL, Adinolfi FG (1985) Megafloral sequence and North American and European correlation of the upper part of the Pottsville Formation of the Warrior coal field, Alabama, U.S.A. In: Escobeda JL, Granádos LF, Melndez B, Pignatelli R, Ray R, Wagner RH (eds) Diéxime Congrés International de Stratigraphie et de Géologie du Carbonifére. Vol. 2: 203–245

McCabe P (1984) Depositional environments of coal and coal-bearing strata. In: Rahmani RA, Flores RM (eds) Sedimentology of Coal and Coal-bearing Sequences. Spec Publ Int Assoc Sedimentol No 7: 147–184

Metzgar WJ (1965) Pennsylvanian stratigraphy of the Black Warrior basin. Alabama Geol Surv Circ 30: 1–80

Pashin JC, Ward WE, Winston RB, Chandler RV, Bolin DE, Hamilton RP, Mink RM (1990) Geologic evaluation of critical production parameters for coalbed methane resources. Gas Research Institute, Annu Rep, Contr No 5087-214-1594: 177 pp

Pashin JC, Osborne WE, Rindsberg AK (1991) Characterization of sandstone heterogeneity in Carboniferous reservoirs for increased recovery of oil and gas from foreland basins. United States Department of Energy Topical Rep, Contr No DE-FG22-90BC1448: 169 pp

Pirkle WA, Pirkle EC (1984) Physiographic features and field relations of Trail Ridge in northern Florida and southeastern Georgia. In: Cohen AD, Casagrande DJ, Andrejko MJ, Best GR (eds) The Okefenokee Swamp: its Natural History, Geology, and Geochemistry. Los Alamos, NM: 613–628

Pody R, Dewey C (1986) Marine facies in the Upper Pottsville: new data from the Black Warrior basin in northern Alabama. Am Assoc Petrol Geol Bull 70: 633

Raymond DE, Rheams LJ, Osborne WE, Gillespie WH, Henry TW (1988) Surface and subsurface mapping for the establishment of a stratigraphic and biostratigraphic framework for the Pennsylvanian section in the Jasper quadrangle of the Black Warrior basin of Alabama: a summary report of investigations for 1986–1987. Alabama Geol Surv Open-File Rep, prepared for the USGS under Agreement No 14-08-001-A0437: 427 pp

Read WA, Forsyth IH (1989) Allocycles and autocycles in the upper part of the Limestone Coal Group (Pendleian E1) in the Glasgow-Stirling region of the Midland Valley of Scotland. Geol J 24: 121–137

Riegel W (1991) Coal cyclothems and some models for their origin. In: Einsele G, Ricken W, Seilacher A (eds) Cycles and Events in Stratigraphy. Springer, Berlin Heidelberg New York: 733–750

Rindsberg AK, Liu Y, Demko TM, Gastaldo RA (1990) Ichnology of a Westphalian coal-bearing sequence in Alabama (Pennsylvanian Warrior basin). 228th International Geological Congress Abstr Vol. 3: 700–701

Seilacher A (1991) Distinctive features of sandy tempestites. In: Einsele G, Seilacher A (eds) Cyclic and Event Stratification. Springer, Berlin Heidelberg New York: 331–349

Tasch P (1973) Paleobiology of Invertebrates. Wiley, New York: 946 pp

Thomas WA (1989) The Black Warrior basin. In: Sloss LL (ed) Sedimentary Cover – North American Craton. The Geology of North America. Vol. A. Geological Society of America, Boulder: 185

Thomas WA, Womack SH (1983) Coal stratigraphy of the deeper part of the Black Warrior basin in Alabama. Gulf Coast Assoc Geol Soc Trans 23: 439–446

Udden JA (1912) Geology and mineral resources of the Peoria Quadrangle, Illinois. US Geol Surv Bull 506: 1 – 103

Van Wagoner JC, Posamentier HW, Mitchum RM, Vail PR, Sarg JF, Loutit TS, Hardenbol J (1988) An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus CK, Hastings BS, Kendall CGStC, Posamentier HW, Ross CA, Van Wagoner JC (eds) Sea-level Changes: an Integrated Approach. Spec Publ Soc Econ Paleontol Mineral No 42: 39 – 45

Van Wagoner JC, Mitchum DM, Campion KM, Rahmanian VD (1990) Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops. Am Assoc Petrol Geol Methods Explor Ser No 7: 1 – 55

Wanless HR, Shepard FP (1936) Sea level and climatic changes related to late Paleozoic cycles. Geol Soc Am Bull 47: 1177 – 1206

Weimer RJ (1984) Relation of unconformities, tectonics, and sea-level changes, Cretaceous of Western Interior, U.S.A. In: Schtee JS (ed) Interregional Unconformities and Hydrocarbon Accumulation. Am Assoc Petrol Geol Mem No 30: 7 – 35

Weller JM (1930) Cyclic sedimentation of the Pennsylvanian Period and its significance. J Geol 38: 97 – 135