Buta, R. J., Rindsberg, A. K., and Kopaska-Merkel, D. C., eds., 2005, Pennsylvanian Footprints in the Black Warrior Basin of Alabama. Alabama Paleontological Society Monograph no. 1.

Pottsville Stratigraphy and the Union Chapel Lagerstätte

JACK C. PASHIN
Geological Survey of Alabama, P.O. Box 869999, Tuscaloosa, Alabama, 35486-6999, USA

ABSTRACT: Amphibian trackways from the Pennsylvanian-aged Pottsville Formation at the Union Chapel Mine are part of a fossil-lagerstätte, or motherlode, that provides exceptional insight into ancient life and environments. The trackways come from the *Cincosaurus* beds, which constitute one of many fossiliferous intervals exposed in the mine. These intervals contain different fossil assemblages representing a spectrum of terrestrial to marine environments of deposition.

The Mary Lee coal bed is a source of low-sulfur coal and represents a widespread peat swamp; it was mined at Union Chapel as a source of high-quality fuel for electric power generation. The *Cincosaurus* beds were deposited on an estuarine mudflat that formed as the Mary Lee swamp was inundated by sediment-laden water. The *Cincosaurus* beds represent a dynamic environment in which amphibians (makers of the trackway *Cincosaurus cobbi*) and a variety of invertebrates ventured onto the mudflat at low tide. Deposition of the *Cincosaurus* beds apparently ended with a drop of relative sea level and widespread soil development. This event was succeeded by a return to peat-swamp sedimentation, as represented by the overlying New Castle coal, which was also mined at Union Chapel. The roof shale of the New Castle coal contains standing fossil forests and represents a swamp that was prone to flooding by mud-laden water. Above the roof shale is a thin bed of nodular limestone containing brachiopods and bivalves, which records a major marine transgression. Above the limestone is a thick, coarsening-upward succession of shale and sandstone that contains marine trace fossils and was deposited in prodelta and delta-front environments during a relative highstand of sea level.

INTRODUCTION

The Union Chapel Mine has yielded a prolific assemblage of amphibian trackways (*Cincosaurus cobbi* Aldrich, 1930) and associated invertebrate trace fossils that provides a unique window into life during Early Pennsylvanian time. The fossil locality at Union Chapel has characteristics of a Konzentrat-Lagerstätte because of exceptional abundance and a Preservat-Lagerstätte because of exceptional preservation of detail (e.g., Seilacher, 1990). The Union Chapel Mine is a surface coal mine in the Warrior coal basin of Walker County, Alabama (Fig. 1). The mine covers parts of the eastern half of sec. 21 and the western half of sec. 22, T. 14 S., R. 6 W. in the Cordova 7.5-minute topographic quadrangle and is excavated into Pennsylvanian-age strata of the Pottsville Formation. Nearly all of the fossil material recovered has come from the mine spoils and, prior to some stabilization and reclamation activities, strata were preserved intact in a highwall that was in places taller than 30 m. Examination of the mine face indicates that strata containing a series of distinctive fossil assemblages were deposited in a wide range of depositional environments that place the trackway discovery into geologic context.

Amphibian trackways have been known from Alabama's coal mines for more than 75 years (Aldrich and Jones, 1930; Rindsberg, 1990), yet little is known about the ancient environments in which the trackways were preserved. The objective of this paper is to characterize the Union Chapel lagerstätte in terms of stratigraphy (i.e., the time-space relationships of sedimentary rock) and environments of deposition. These strata provide evidence for local conditions as the trackways formed and also provide a compact record of the tectonic and climatic processes that operated globally as continental masses came together to form the supercontinent Pangaea.

Characterization of the Union Chapel lagerstätte underscores the relevance of geology to our everyday lives and demonstrates that fossil finds are not merely academic curiosities. The Pottsville Formation is an important source of coal and natural gas that are used for many purposes, including electric power generation, metallurgy, and home heating. Geologists routinely characterize the paleontology, stratigraphy, and sedimentology of these strata to predict the distribution, quantity, and quality of coal and natural gas resources, thereby ensuring a stable supply of energy for the future.

POTTSVILLE FORMATION

Economic coal-bearing strata in Alabama are restricted mainly to the Pottsville Formation of Early Pennsylvanian age (Morrowan Epoch), which has been dated using fossil spores and marine invertebrates (Butts, 1926; Eble and Gillespie, 1989; Eble et al., 1991). The Union Chapel Mine is in the Warrior coal basin, which underlies most of Walker, Jefferson, and Tuscaloosa counties and includes nearly 90 percent of Alabama's bitumi-

FIGURE 1. Location of the Union Chapel Mine in the bituminous coal fields of Alabama.

nous coal resources (Ward, 1984) (Fig. 1). The Pottsville Formation contains mainly shale, sandstone, and bituminous coal, and the total thickness of the formation approaches 2 km in the Warrior coal basin (McCalley, 1900; Butts, 1926; Thomas, 1988) (Fig. 2). Coal resources are estimated to exceed 21 billion metric tons (Ward, 1984), and demonstrated reserves are nearly 4 billion metric tons (Carroll, 1997). McCalley (1900) recognized that coal beds in the Alabama Pottsville are concentrated in stratigraphic clusters which he called coal groups. Coal groups, which are properly termed coal zones to avoid confusion with formal stratigraphic nomenclature, have formed the basis of most subsequent stratigraphic subdivisions of the Pottsville Formation (e.g., Butts, 1910, 1926; Culbertson, 1964; Metzger, 1965).

The lower Pottsville Formation is dominated by sandstone and contains few mineable coal beds, whereas the upper Pottsville contains nearly all of the coal reserves in the Warrior coal basin (Fig. 2). Within the upper Pottsville, the Black Creek, Mary Lee, Pratt, and Brookwood coal zones are economically most important. More than two thirds of the 19.3 million short tons of coal mined in Alabama during 2001 came from the Blue Creek and Mary Lee beds of the Mary Lee coal zone (R.E. Carroll, personal commun., 2002), which includes the Union Chapel Mine.

Nearly 12 million short tons of coal was produced from deep underground mines in the Blue Creek and Mary Lee coal beds between depths of 300 and 700 m during 2001. These mines include the deepest vertical shaft underground coal mines in North America, and the high natural gas content of these coal beds has been an acknowledged mining hazard since the 19th century (McCalley, 1886; Butts, 1926). During the 1970s, the U.S. Bureau of Mines investigated the possibility of producing natural gas from Blue Creek coal to improve mine safety (Elder and Deul, 1974), and thus the modern coalbed methane industry, which now spans the globe, was born in Jefferson County, Alabama. Annual coalbed methane production exceeds 3 Bcm (billion cubic meters), and cumulative production exceeds 35 Bcm. Coalbed methane resources (i.e., the total amount of gas in the coal) in west-central Alabama are estimated between 280 and 570 Bcm (Hewitt, 1984; McFall et al., 1986) and, according to the U.S. Geological Survey, reserves (i.e., the amount of that gas that is recoverable using current technology) exceed 100 Bcm (J. R. Hatch, personal communication, 2002). Commercial production of coalbed methane began from the Mary Lee coal zone in 1980, and today natural gas is produced from the Black Creek through Utley coal zones (Pashin and Hinkle, 1997). Alabama remains a world leader in the development and application of coalbed methane technology. Today, coalbed methane accounts for about 25 percent of the natural gas produced in Alabama, and the state ranks 9th nationally in natural gas production.

In addition to being a source of natural gas, coal is a potential sink for greenhouse gases, such as carbon dioxide. Bituminous coal can hold about twice as much carbon dioxide as methane, and injection of carbon dioxide into coal through wells has the potential to increase coalbed methane recovery (e.g., Reichle et al., 1999; Gentzis, 2000). In a preliminary investigation of the Warrior coal basin, Pashin et al. (2001) suggested that potential exists to sequester more than 35 years of greenhouse gas emissions from coal-fired power plants serving the Birmingham-Tuscaloosa area.

TECTONICS AND PALEOCLIMATE

The late Paleozoic was a time of major plate-tectonic and climatic changes associated with the assembly of Pangaea (Fig. 3). During this time, ancestral North America and Europe, or Laurussia, collided with a large continental mass called Gondwana. Plate reconstructions suggest that tectonic activity in southeastern Laurussia was related to closure of a small Mediterranean-type ocean basin called the Rheic Ocean (e.g., Scotese, 1990; Scotese et al., 1994). As this basin closed, the Laurussian plate drifted northward, and what is now the Warrior coal basin moved from a latitude of about 25° S, which is in the arid southern tradewind belt, to a latitude of

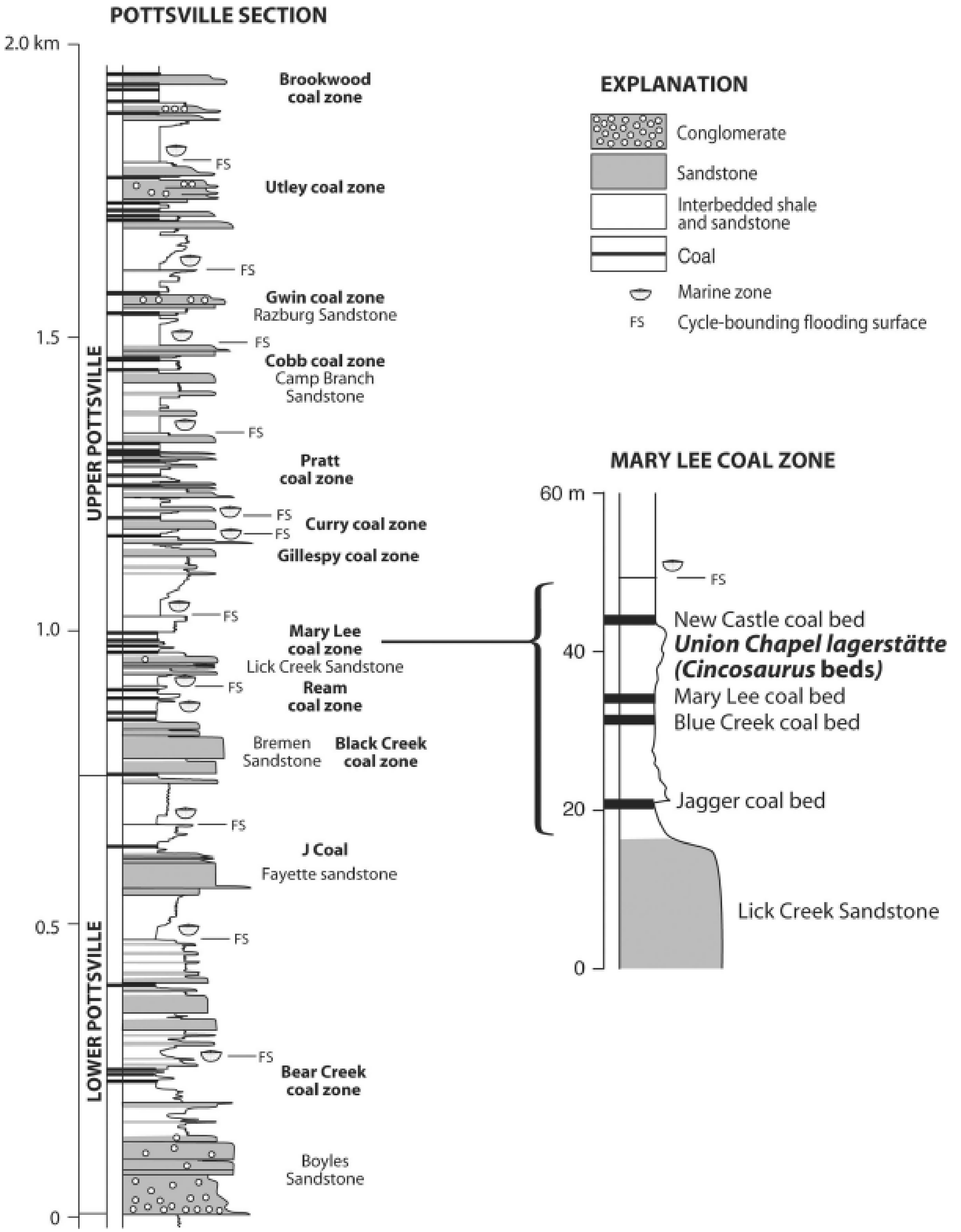

FIGURE 2. Generalized stratigraphic section of the Pottsville Fomation in the Warrior coal basin showing stratigraphic position of the Union Chapel lagerstätte.

about 10° S, which is in the humid equatorial belt. In eastern North America, including the Warrior coal basin, this humidification is reflected partly by the occurrence of Bahama-type limestone banks of Mississippian age followed by widespread peat (i.e., coal) swamps of Pennsylvanian age (Cecil, 1990; Pashin, 1994a).

Although the Warrior coal basin was near the paleoequator, the Gondwanan continental mass was centered on the South Pole and provided a nucleus for a major continental ice sheet that waxed and waned from Late Devonian through Middle Permian time (Caputo and Crowell, 1985; Frakes et al., 1992)(Fig. 3). Depositional cyclicity is a salient feature of Pennsylvanian-age rocks, and sea-level changes recorded by these cycles have long been thought to have been driven by waxing and waning of the Gondwanan ice sheet (e.g., Wanless and Shepard, 1936; Heckel, 1986). Glacially driven sea-level change probably exceeded 40 m in magnitude during the Early Pennsylvanian (Maynard and Leeder, 1992). Numerous marine-nonmarine depositional cycles have been identified in the Pottsville Formation, and the high frequency of these cycles appears to be compatible with glacially driven sea-level change (Pashin, 1994a, 1994b).

The Warrior coal basin is part of a larger sedimentary basin called the Black Warrior Basin (Fig. 4). Sedimentary basins that form adjacent to collisional mountain ranges, or orogenic belts, are called foreland basins. The Black Warrior Basin formed at the juncture of the Appalachian and Ouachita orogenic belts, which intersect at near right angles (Mellen, 1947; Thomas, 1977, 1985) (Fig. 4). The crust of the earth thickens in the collision zones where orogenic belts form and, to compensate for the load of this thickened crust, the adjacent crust flexes downward, and a foreland basin is formed (Fig. 5). Uplifting mountains also provide source areas for sediment, which can be eroded from the orogenic highlands and deposited in the adjacent foreland basin.

The Black Warrior Basin formed on a prominence of the Laurussian continental platform called the Alabama promontory (Thomas, 1977, 1985) (Fig. 4). The Ouachita orogen formed by collision on the southwest margin of the promontory, whereas the Appalachian orogen formed on the southeast margin. According to Thomas (1974, 1976, 1985), the Black Warrior Basin began forming in Late Mississippian time (~335 Ma [million years ago]) with the inception of Ouachita orogenesis on the southwest part of the Alabama promontory. Although the Appalachian orogen began forming during Ordovician time (~450 Ma), early tectonic activity was remote to the Black Warrior Basin. Consequently, sedimentation driven by Appalachian orogenesis did not affect the eastern Black Warrior basin until Pottsville deposition (~315 Ma), when a new, more localized downwarp was superimposed on the still-active Ouachita foreland basin (Pashin et al., 1991; Pashin, 1994b).

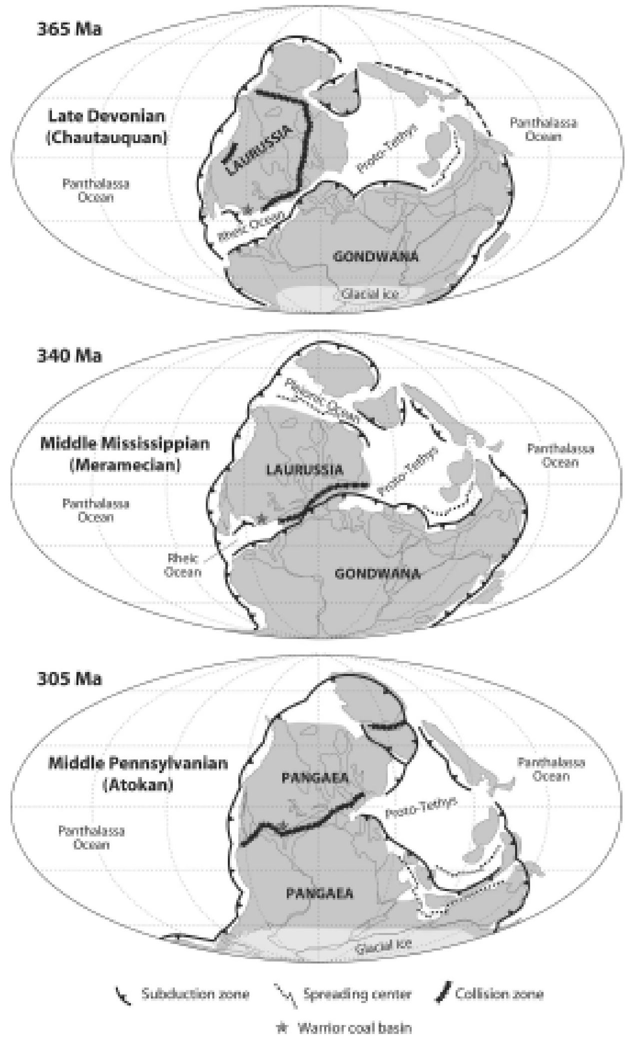

FIGURE 3. Generalized plate reconstructions for Devonian through Pennsylvanian time showing formation of Pangaea, northward drift of ancestral North America, and generalized location of the Gondwanan ice sheet (after Scotese, 1990).

POTTSVILLE DEPOSITIONAL ENVIRONMENTS AND CYCLES

Following establishment of the basic stratigraphic framework by McCalley (1886, 1900), Butts (1926) recognized the evidence for repeated marine transgressions and regressions during Pottsville deposition. During the mid-20th century, studies of coal-bearing strata in the eastern United States focused on depositional cyclicity, which is a salient characteristic of Pennsylvanian-age sedimentary rocks (e.g., Weller, 1930; Wanless and Shepard, 1936). During this time, however, little work was done on the Alabama Pottsville. In the 1960s, models of modern depositional environments and sedimentary sequences began emerging that encouraged investigators to piece together the details of Pottsville stratigraphy and sedimentation in Alabama and to provide new perspectives on Pennsylvanian coal-bearing strata.

Ferm et al. (1967) explained the heterogeneous distribution of shale, sandstone, and coal in the Pottsville Formation by developing a depositional model based on sedimentary processes in coastal and shallow marine environments. This model signaled a shift in thinking

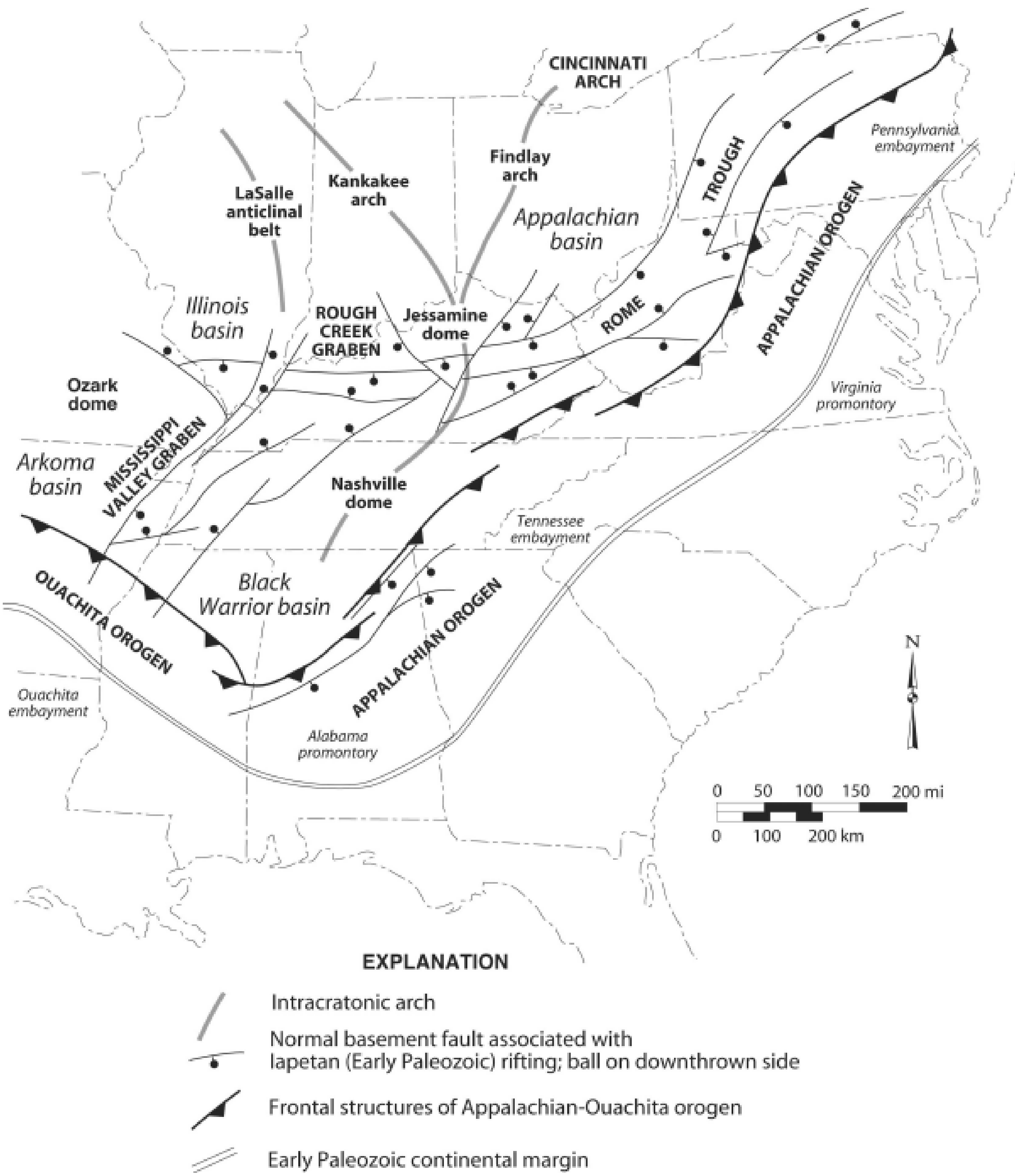

Figure 4. Tectonic setting of the Black Warrior basin (after Thomas, 1998).

toward paleoenvironmental modeling in the coal-bearing successions of the Appalachian region, and subsequent investigators have interpreted the Pottsville Formation within this general framework (e.g., Hobday, 1974; Horsey, 1981; Rheams and Benson, 1982; Thomas, 1988; Ferm and Weisenfluh, 1989) (Figs. 6, 7).

Exploration for oil and gas in the Black Warrior basin has had a strong influence on recent interpretations of Pottsville stratigraphy and sedimentation. Subsurface studies by Thomas and Womack (1983) and Sestak (1984) indicated that the Ouachita orogen was an important source of fluvial (i.e., riverine) and deltaic

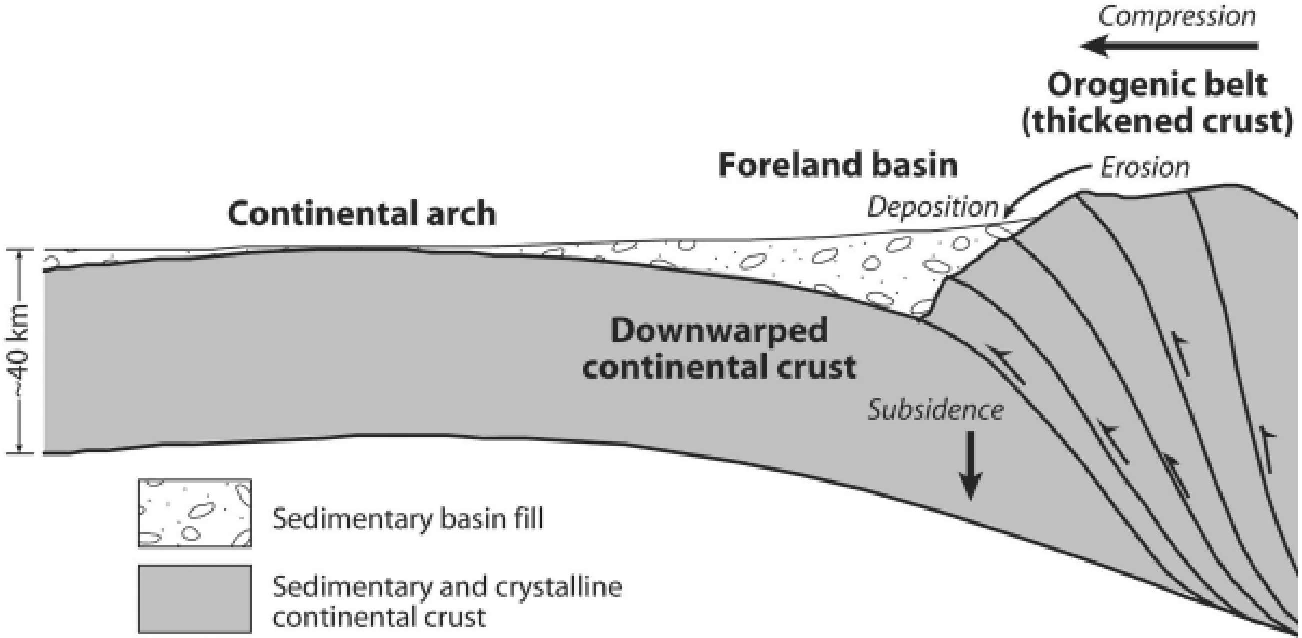

FIGURE 5. Diagram showing flexure of the earth's crust adjacent to mountain ranges to form foreland basins.

sediment during Pottsville deposition and confirmed that the upper Pottsville coal zones could be traced across the basin. Intensive coalbed methane development in the eastern Black Warrior basin provided new data indicating that the Appalachian orogen was a more important source of sediment than was previously thought (Pashin et al., 1991; Pashin, 1994a).

While recognizing the extreme vertical and lateral heterogeneity of the Pottsville Formation, Pashin et al. (1991) found that the Pottsville Formation contains regionally extensive depositional cycles ranging in thickness from 10 to 200 m. Each cycle contains (1) a marine shale unit at the base, (2) a fluvial-deltaic or barrier-shoreline sandstone near the middle, and (3) a lithologically heterogeneous coal zone of fluvial-deltaic origin at the top (Figs. 2, 6). Recent investigators have applied the concepts and nomenclature of sequence stratigraphy (Vail, 1987; Galloway, 1989) to the Pottsville cycles (e.g., Gastaldo et al., 1993; Pashin, 1998). Contacts between cycles are typically sharp or intensely burrowed by animals and have been interpreted as major marine flooding surfaces by Liu and Gastaldo (1992). The flooding surface is characteristically overlain by a thin (<1 m) interval of limy shale or clayey to sandy limestone containing a condensed marine fossil assemblage dominated by brachiopods, molluscs, and crinoids (e.g., Gibson, 1990). Such condensed assemblages form in response to reduced sedimentation rate during the most rapid parts of marine transgressions (i.e., marine flooding events).

The thick mudstone unit (10-75 m) in the lower part of each cycle is dark gray and coarsens upward into sandstone; the shale is considered to represent constructive deltaic systems that marched basinward during relative highstands of sea level (Gastaldo et al., 1993; Pashin, 1998) (Figs. 6, 7). Sandstone and conglomerate units near the middle of the cycles are medium to light gray and very fine- to coarse-grained; they represent diverse depositional environments including deltaic deposits, incised valley fills, beach-barrier systems, and marine sand banks. Although much of the deltaic sandstone was deposited during relative highstands, most of the beach-barrier and incised valley deposits were deposited following lowstands. The economic coal zones forming the top of most cycles represent a spectrum of coastal plain environments, including muddy estuaries and destructive deltaic systems that were deposited mainly during the early stages of marine transgression.

Pashin (1994a) suggested that the upper Pottsville depositional cycles each represent an average timespan of less than 0.5 my (million years), which is compatible with the high-frequency global changes of sea level associated with Gondwanan glaciation. Waxing and waning of continental ice sheets is thought to be regulated by Milankovitch orbital parameters, which refer to periodic changes in the earth's orbit around the sun (Imbrie and Imbrie, 1980; Imbrie, 1985) (Fig. 8). Variation of insolation (incident solar radiation; Berger and Loutre, 1991) in concert with the long eccentricity cycle (ellipticity of earth's orbit; 0.4 my) is commonly cited as the cause for depositional cyclicity during Pennsylvanian time (Heckel, 1986, 1994) (Fig. 9). However, the oxygen isotope record indicates that the short eccentricity (~0.1 my) and obliquity cycles (~0.04 my) dominated Pleistocene glaciation (Imbrie and Imbrie, 1980; Rial, 1999). Pashin et al. (2003) discovered that three minor flooding surfaces of regional extent can be traced within many Pottsville cycles, which suggests the short eccentricity signal (Fig. 10). Accordingly, they interpreted that falling sea level in the short eccentricity band contrib-

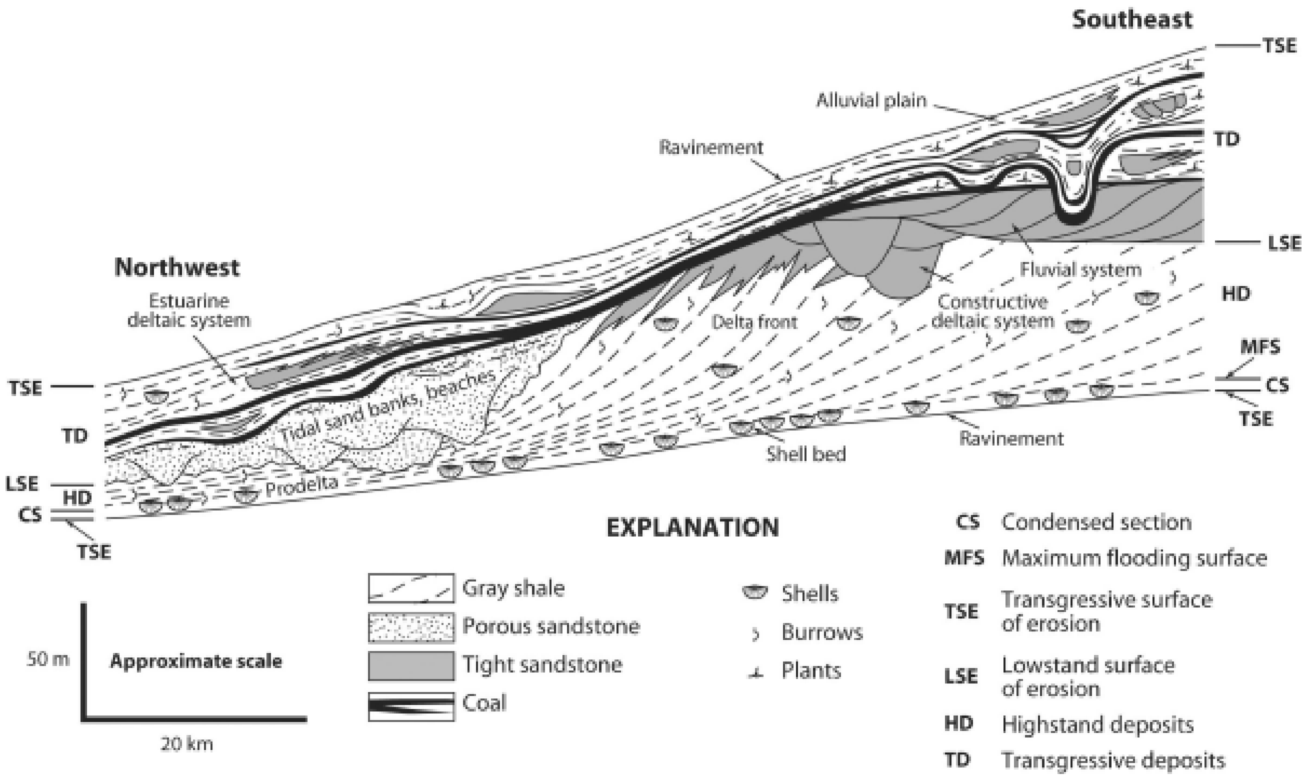

FIGURE 6. Idealized Pottsville depositional cycle in the Black Warrior Basin of Alabama (after Pashin, 1998). Ravinement surfaces and condensed sections apparently formed during the most rapid parts of relative sea level rises. Constructive delta deposits formed during times of high relative sea level, whereas the major coal zones include alluvial plain and estuarine delta deposits that apprently formed during the early stages of sea-level rise.

uted to incision of river channels and valleys at multiple stratigraphic levels within each cycle. By the same token, rising sea level favored high water table conditions and formation of the widespread peat swamp complexes which have been preserved as coal beds.

THE UNION CHAPEL SECTION

The Union Chapel Mine covers approximately two square kilometers in the Cordova 7.5-minute quadrangle. The Pottsville Formation is approximately 400 m thick in this area, and the Mary Lee coal zone spans about 30 m of section (Metzger, 1965; Tolson, 1986). Strata exposed in the mine face include the upper part of the Mary Lee coal zone and the thick marine mudstone below the Gillespy coal zone (Figs. 2, 11). Effectively all of the *Cincosaurus cobbi* trackways collected at the mine came from the mine spoils, thus careful examination of the mine face is required to identify the beds in which they originated.

The following discussion is based on a description and measured section of the mine face that was made using standard field procedures (e.g., Lahee, 1961). The section was measured on August 8, 2000, during a field trip of the Birmingham Paleontological Society. Additional information on the geologic setting of the mine and the quality of the coal was derived from mine records in the open files of the Geological Survey of Alabama.

Mary Lee Coal Bed

Characteristics. The Mary Lee coal zone contains four named coal beds, which in ascending order are the Jagger coal, the Blue Creek coal, the Mary Lee coal, and the New Castle coal (Fig. 2). The Jagger and Blue Creek beds are absent in the Cordova Quadrangle, and so the Mary Lee and New Castle beds are the chief mining targets in the Union Chapel area (Tolson, 1986). Although the coal was concealed below talus when the section was measured, mine records indicate that the Mary Lee bed maintains a uniform thickness of 0.6 m in and around the Union Chapel Mine.

The Mary Lee coal in the Union Chapel area is bright-banded in hand sample and contains no significant partings of shale or sandstone (Tolson, 1986). Microscopic examination of coal banding reveals that the Mary Lee coal in Walker County contains a diverse flora dominated by lycopods (treelike club mosses), calamiteans (horsetail-like sphenophytes), and fernlike foliage (Winston, 1990; Eble et al., 1994) (Fig. 12). Thick, bright bands in coal are called vitrain and consist of coalified woody material, including the axes, branches, and roots of coal-forming plants. Hard, dull coal bands are called clairain and durain and are dominated by macerated woody debris, leaf litter, and spores. Fusain forms very soft, dull bands in coal that resemble charcoal and consists of intensely oxidized plant remains.

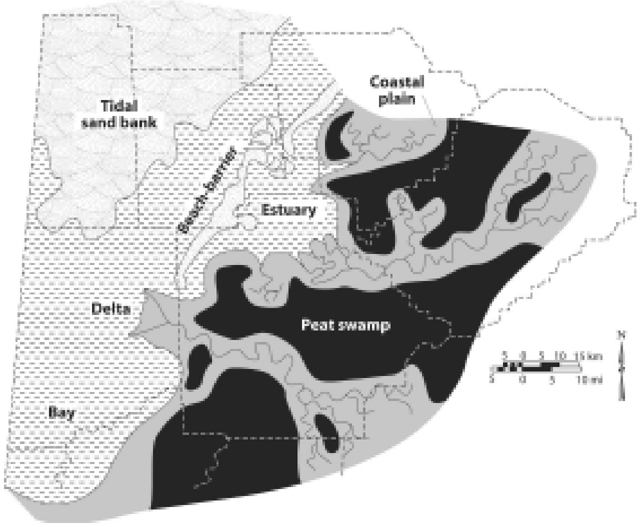

FIGURE 7. Generalized upper Pottsville paleogeography in the Black Warrior basin of Alabama (after Pashin et al., 1991).

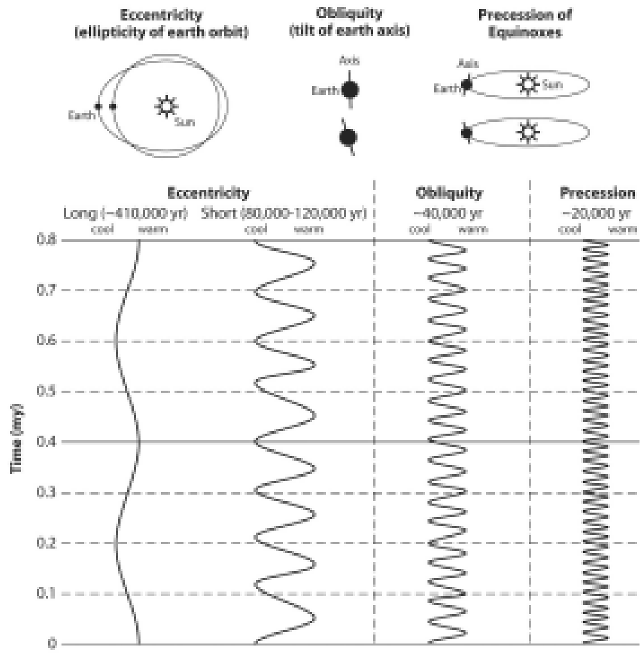

FIGURE 8. Idealized climatic cycles related to Milankovitch orbital parameters.

The Mary Lee coal is of exceptional quality, having a heating value of about 12,000 Btu/lb, ash content between 13 and 16%, and only 0.4 to 0.9% total sulfur (Bragg et al., 1998). The high heating value and low sulfur content of the coal makes it an attractive fuel for electric power generation.

Interpretation. The Mary Lee coal bed represents a widespread peat swamp that formed on the Pottsville coastal plain. The composition and quality of the coal reveals that the Mary Lee swamp was a dynamic environment consisting of a lycopod forest with an understory of sphenophytes and fernlike foliage (Winston, 1990; Eble et al., 1994) (Fig. 12). Vitrain, clarain, and durain bands preserve plants and forest litter, whereas intensely oxidized plant material in fusain bands provides evidence for swamp fires that occasionally ravaged the lycopod forest. Plants are compressed greatly to make coal, and in Appalachian coal beds, peat is thought to have compacted by a factor of 10 (Cobb et al., 1981; Pashin, 1994c). Accordingly, the original thickness of Mary Lee peat at the Union Chapel Mine was about 6 m.

Coal ash is the non-combustible portion of coal and consists mainly of mineral matter, such as pyrite, clay, and quartz. Mineral matter can be introduced into coal by flooding, wind, volcanic eruptions, and chemical reaction (Spears, 1987). Some mineral matter may be derived directly from plants in the form of platelets called phytoliths (Renton and Cecil, 1979). Volcanic ash layers have not been identified in the Warrior coal basin, thus most clay and quartz in Alabama coal was introduced by flooding and perhaps to a minor extent by wind.

Peat swamps can be classified as domed or low-lying (e.g., McCabe, 1984). Peat domes are mounds that are protected from flooding and thus can have ash content lower than 2 percent. Today, tropical peat domes are forming in southeast Asia (Anderson, 1964; Staub and Esterle, 1994). By contrast, low-lying swamps are prone to flooding with sediment-laden water and therefore can contain peat with higher ash content. The relatively high ash content of the Mary Lee coal in the Union Chapel area suggests that peat accumulated in a low-lying swamp. The lack of shale partings in the coal further indicates that it formed in interior parts of the swamp that were protected from overbank sedimentation. Low-lying swamps are common in the southeastern United States and include the well-known Okefenokee Swamp of Georgia (Cohen, 1974).

Sulfur not only is a major determinant of the marketability of coal, but it also provides important information on depositional setting (Casagrande, 1987). The primary forms of sulfur in coal are organic sulfur and pyritic sulfur. Organic sulfur is bound to the coal structure and is thought to be derived mainly from coal-forming plants. Pyritic sulfur is in iron sulfide (pyrite; FeS_2) and is thought to be primarily the product of bacterial sulfate reduction in peat. Sea water is saturated with sulfate, and coal with sulfur content higher than 2 percent is typically overlain directly by marine strata (Williams and Keith, 1963). Organic sulfur content in the Warrior coal basin averages 0.1 percent and does not correlate significantly with total sulfur, whereas pyritic sulfur correlates strongly with total sulfur (Pashin et al., 2003). The low sulfur content of the Mary Lee bed in the Union Chapel area indicates that the peat contained only fresh water during early burial.

Cincosaurus Beds

Characteristics. Comparison of the slabs containing *Cincosaurus cobbi* with the mine face indicates that all amphibian trackways found at the Union Chapel Mine

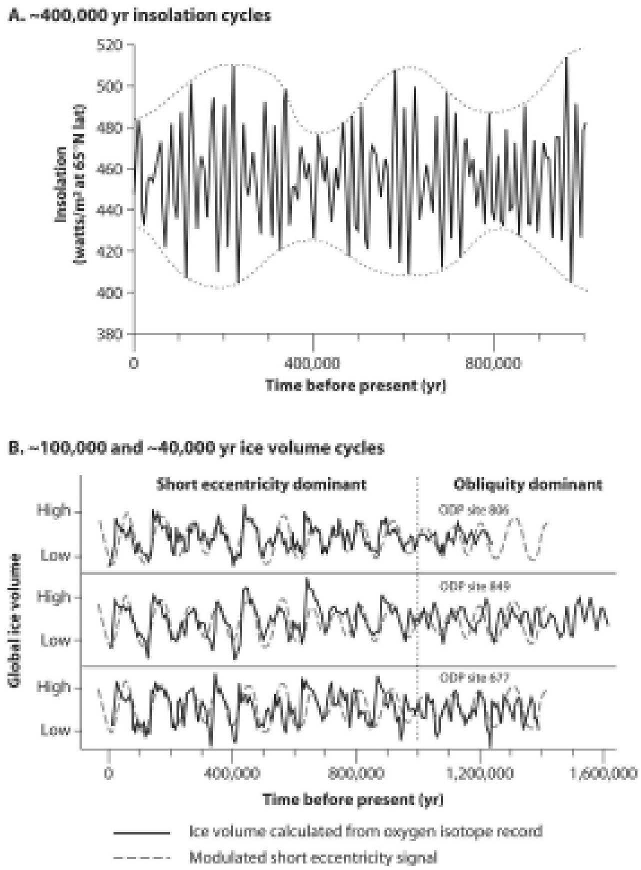

FIGURE 9. Variation of insolation and ice volume during the Pleistocene glaciation (after Berger and Loutre, 1991; Riall, 1999).

came from the interval of dark gray shale between the Mary Lee and New Castle coal beds. Accordingly, this interval is named the *Cincosaurus* beds (Fig. 11). The lower 4 m of this interval is dominated by pinstripe-bedded mudstone (see Klein, 1977). The mudstone comprises numerous siltstone-shale and sandstone-shale beds that are normally graded (i.e., fine upward) and range in thickness from 0.2 cm to more than 4.0 cm (Figs. 13, 14). Siltstone and sandstone form thin, light gray laminae at the bases of most graded beds, and dark gray graded mudstone forms the bulk of the beds. All trackways are preserved as impressions at the tops of the graded beds (Fig. 15) or as casts (undertracks) at the bases.

Progressive thickening and thinning of successive graded beds is common in the *Cincosaurus* beds (Fig. 13A). Locally, thick and thin beds are paired to form couplets (Fig. 13B). Examination of the highwall indicates that the graded beds pinch and swell laterally. In some areas, siltstone-shale beds thicker than 2 cm thin to less than 0.5 cm in a distance of about 5 m. Broad (>5 m), shallow (<0.3 m) scour surfaces also are common in the *Cincosaurus* beds. The thickness of 126 successive beds was measured near the north end of the highwall, and a bar chart demonstrates progressive thickening and thinning of the graded beds (Fig. 14). Although thickness changes appear to be largely progressive, the minima and maxima of layer thickness are irregularly spaced.

Some types of physical sedimentary structures are common in the *Cincosaurus* beds. Sole markings are on the bases of some graded siltstone-shale and sandstone-shale beds and include groove casts, prod marks, and load casts. The most distinctive physical structures are crater-like impressions at the top of the graded shale beds (Fig. 15). These impressions have variable size and spacing and are characterized by elevated circular rims around central depressions.

Several types of trace fossils are preserved with *Cincosaurus,* including probable horseshoe crab traces (*Kouphichnium* isp.), fish traces (*Undichna* isp.), insect traces (*Treptichnus* isp.), and millipede traces (*Diplichnites* isp.). These traces are illustrated in detail in Buta et al. (2005) and have been identified in other Pottsville exposures (Rindsberg, 1990). Macerated plant debris is common on bedding planes, and most plant fossils in the *Cincosaurus* beds include fragments of fronds and branches derived from seed ferns (*Neuropteris* sp.) and other fern-like foliage, as well as the horsetail-like sphenophyte *Calamites* sp. In the northern part of the mine face, an erect seed fern stump was observed, and several erect specimens of *Calamites* have been recovered from the spoils.

The upper 2 m of the *Cincosaurus* beds contrast sharply with the underlying pinstripe-bedded shale that yielded the trackways (Fig. 11). Above the pinstripe-bedded interval is about 1 m of ripple-bedded (wavy and flaser-bedded) sandstone and shale. The sandstone is very fine grained and light gray, whereas the shale is silty. Discoid pebbles of shale and siderite are common in this bed, as are tubular horizontal burrows of unknown affinity. The uppermost meter of the *Cincosaurus* beds consists of sandy underclay that fines upward. Siderite nodules and root traces are common throughout the underclay interval, and some root traces extend downward into the ripple-bedded sandstone below. Siderite nodules are distinctive because they are hard and have reddish hues. The root traces are assigned to the genus *Stigmaria,* which is the root system of a variety of lycopod types.

Interpretation. The *Cincosaurus* beds are interpreted as intertidal mudflat deposits (Fig. 11), and these types of deposits have been known from the Pottsville Formation for many years (Hobday, 1974; Demko and Gastaldo, 1996). The *Cincosaurus* mudflat formed by inundation of the Mary Lee peat swamp with sediment-laden water, and biogenic and physical structures reveal much about the dynamics of the environment where the trackways were preserved. Peat compacts greatly during the early stages of burial below mud and sand (Nadon, 1998), so preservation of the *Cincosaurus* beds may reflect accumulation of sediment above compacting peat as much as rising water level.

The graded siltstone-shale and sandstone-shale beds (Fig. 13) indicate that sedimentation was episodic. Each graded bed represents a single event in which sediment settled from suspension in water at the site of deposition. Groove casts and prod marks formed prior to depo-

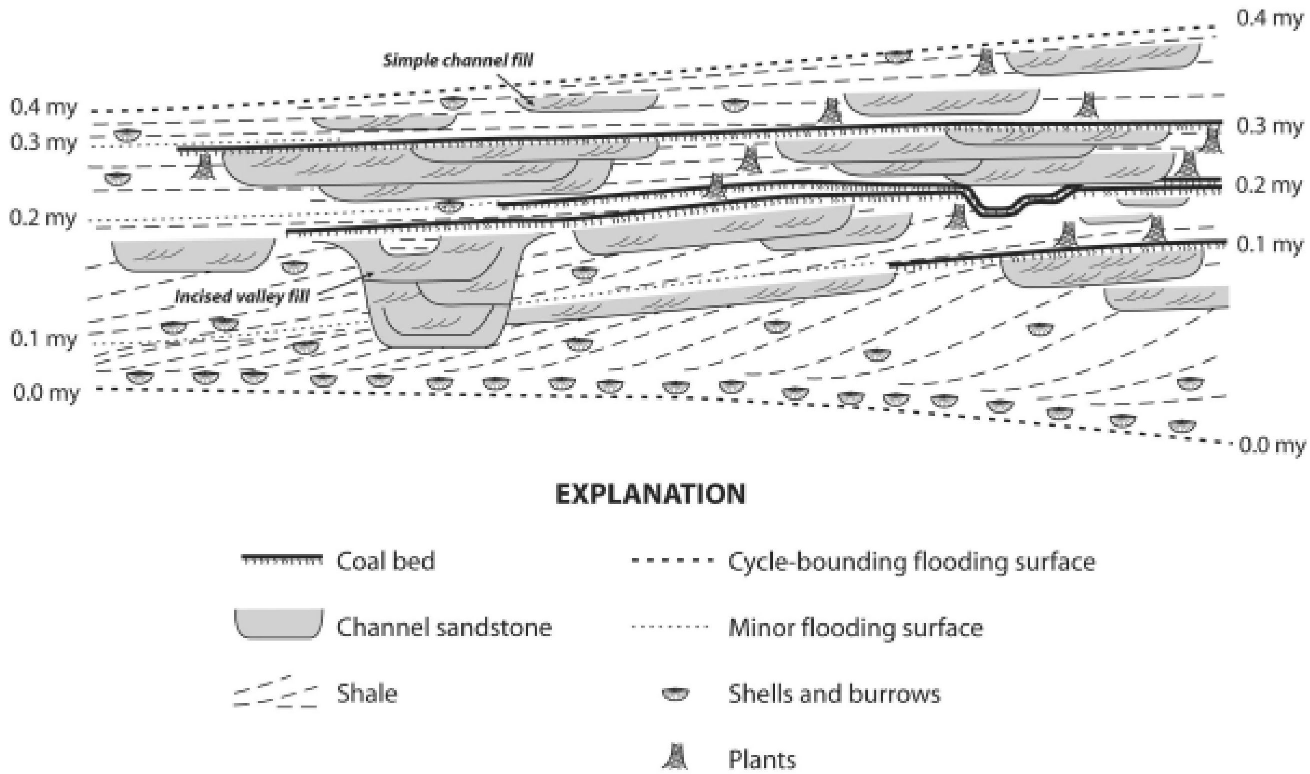

FIGURE 10. Idealized relationship of stratigraphic variation within a Pottsville depositional cycle to 0.1 Ma eccentricity cycles (after Pashin et al., 2003).

sition as vigorous currents caused objects to slide or skip on the sediment surface. Load casts, by comparison, formed later as fluid sediment deformed under the weight of the younger graded beds. Sand and silt settled first from suspension as the current slowed, and the lighter clay settled later, thus forming graded beds. Paired thick and thin graded beds correspond to paired events in which the current depositing the thick bed was stronger. Such paired depositional events are common in tidal systems and can represent the deposits of flood (incoming) and ebb (outgoing) tides. Evidence for the tidal range is not preserved at the Union Chapel Mine, but comparison of Pottsville strata with modern analogs suggests that a mesotidal regime (2-4 m) prevailed during Pottsville deposition (Hobday, 1974; Horne, 1979).

Progressive thickening and thinning of bedding is common in Pennsylvanian-age tidal deposits, and analysis of bedding thickness patterns has been used to characterize monthly (spring-neap) tidal cycles (e.g., Kvale et al., 1989; Archer, 1991). Pashin et al. (1995) and Pashin and Carroll (1999) identified 14-part cycles of bedding thickness in graded strata resembling the *Cincosaurus* beds in Jefferson County, Alabama. They suggested that these cycles are the product of a dominantly diurnal lunar tidal regime (one flood daily) and that each cycle represents 2 weeks. Diurnal systems are typical of embayments that are restricted from the resonance of the open ocean, and this type of tidal system exists today in the Gulf of Mexico. Statistical analysis of the *Cincosaurus* beds indicates poor preservation of spring-neap cyclicity at the Union Chapel Mine (Fig. 16). The dominant periodicity of the thickness cycles is 31.2 layers, and subordinate frequencies include 62.5, 17.8, and 10.4 layers. These cycle periods suggest that spring-neap cycles were masked by other depositional processes, and the frequencies of 62.5 and 31.2 may indicate monthly, seasonal, or even localized changes of sediment flux. This result is not surprising because bedding in the *Cincosaurus* beds pinches and swells laterally, and broad scour-and-fill structures provide firsthand evidence for discontinuous sedimentation.

The extremely low sulfur content of the Mary Lee coal bed indicates that the waters that inundated the swamp were fresh and, indeed, modern amphibians have effectively no tolerance for saline conditions. Therefore, the *Cincosaurus* beds can be interpreted as an estuarine mudflat in which tidal currents primarily moved fresh water about. Other fresh-water tidal deposits have been identified in the roof of Pennsylvanian-aged coal in Indiana by Kvale and Mastalerz (1998), and estuarine mudflats exist today adjacent to low-ash peat swamps on the Rajang Delta in Indonesia (Staub and Esterle, 1994) (Fig. 17). Using the Rajang Delta as a modern analog, sedimentation on the *Cincosaurus* mudflat may have been influenced as strongly by changes in stream levels and deltaic sediment discharge as by spring-neap tidal cycles.

Interpretation of the craterlike impressions is problematic. These structures resemble raindrop imprints, and if this interpretation is correct, the circular outlines indicate that the drops fell under low-wind conditions (Reineck, 1955; Shrock, 1948). Raindrop imprints are

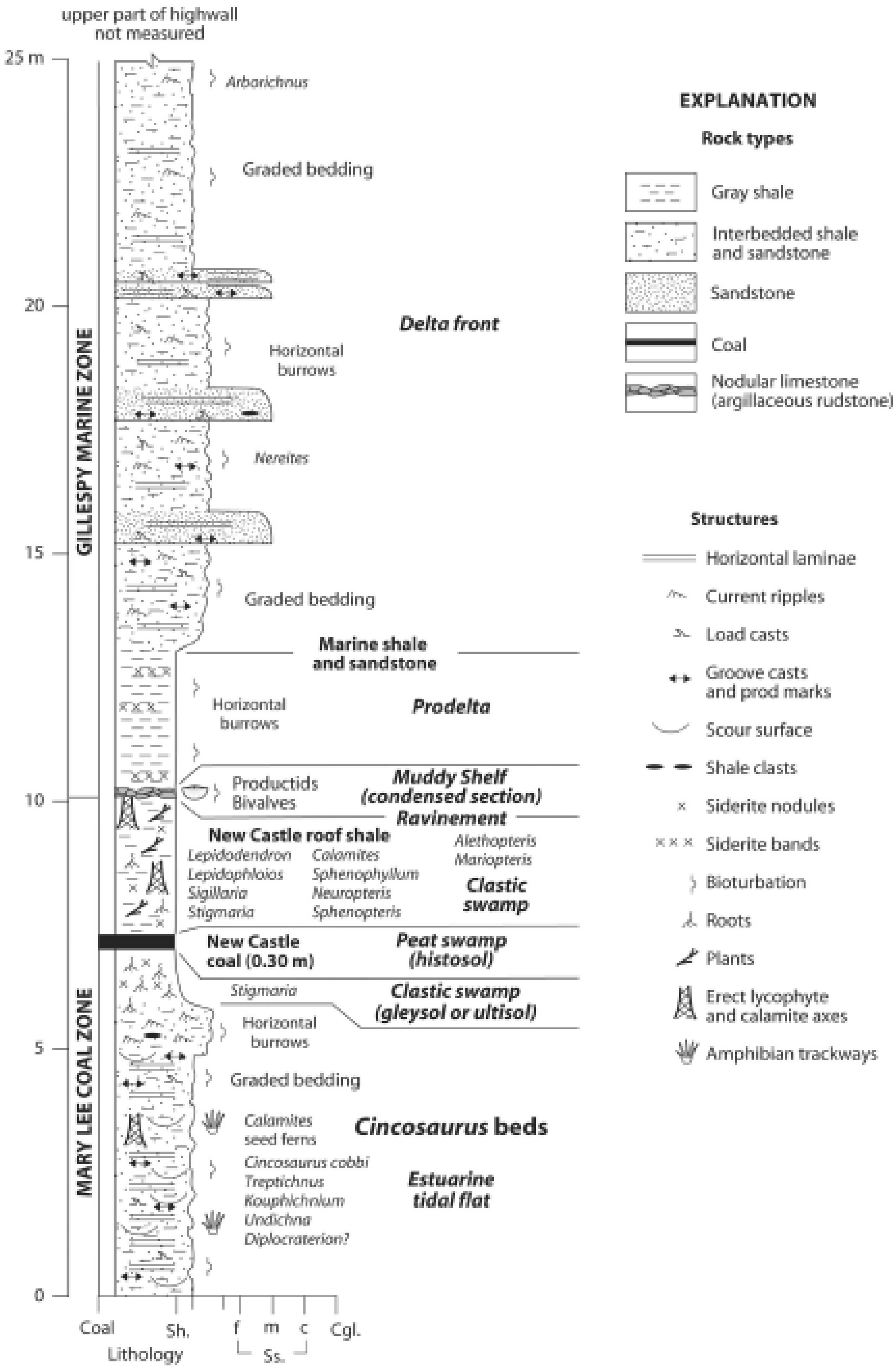

FIGURE 11. Measured section of the Pottsville Formation at the Union Chapel Mine.

compatible with the rainy, equatorial setting of the Pottsville Formation. A lack of mudcracks indicates that the mud flat was never exposed long enough for the sediment to desiccate and crack; thus windows of opportunity for the formation of raindrop imprints were restricted to extreme low-tide conditions. However, many of these structures have irregular outlines or appear stretched, suggesting that an origin as collapsed gas bubbles is more feasible in many cases (see Rindsberg, 2005). Also, few of the structures overlap, which is atypical of raindrop imprints, and some of the structures appear to pass through multiple layers and may, therefore, include an

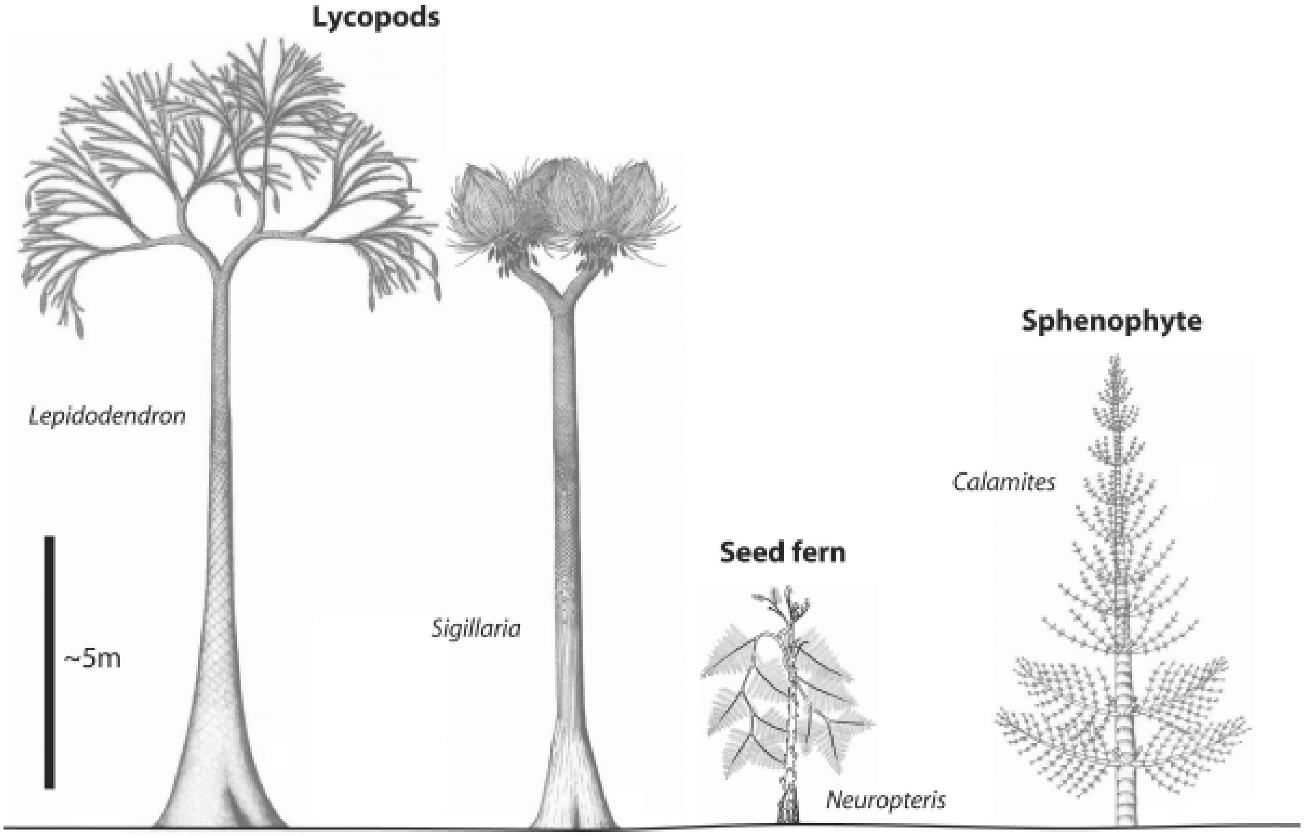

FIGURE 12. Reconstructions of common plant fossils in Pennsylvanian-aged coal-bearing strata (after Gillespie et al., 1978).

enigmatic type of burrow.

Calamites and an unidentified seed fern were the only plants preserved in life position in the *Cincosaurus* beds. The mangrove-like root systems of seed ferns (Fig. 12) attest to frequent flooding of the mud flat and suggest analogy with modern mangrove swamps of the muddy shore zone. Whereas some plants resided on the mud flat, the trace fossil assemblage is dominated by locomotion traces, indicating that most fauna were in transit. One possibility is that during low-water conditions, *Cincosaurus* and other creatures entered the mud flat to forage.

The ripple-bedded sandstone and shale near the top of the *Cincosaurus* beds also is characteristic of tidal flats (e.g., van Straaten, 1954) and, based on the overall lithologic character of this interval, it can be interpreted as the deposit of a mixed sand-mud flat. Ripple-bedded sandstone indicates deposition by turbulent flow, whereas the shale represents mud that accumulated during low-flow or slack-water conditions. One possibility is that the ripple-bedded sandstone and shale were deposited in a sandier part of the same mudflat complex where the *Cincosaurus* trackways were preserved.

The underclay at the top of the *Cincosaurus* beds marks a transition from tidal flat to swamp environments, thus foreshadowing formation of the overlying New Castle coal. Intense rooting in underclay beds provides evidence for formation of an ancient soil horizon, or paleosol. Underclay beds generally are interpreted as hydromorphic paleosols, which are subaqueous wetland soils, but the complete origin of underclay beds is imprecisely known and is controversial (e.g., Gardner et al., 1988; Mack et al., 1993). Most investigators agree that underclay formation began with a lowered water table in which iron and other compounds were leached from the upper part of the soil profile. In Pottsville underclay, the leached iron is preserved in the lower part of the ancient soil profile as siderite nodules. As the water table rises, perhaps in concert with sea level, a swamp forest can be established and, as wetland conditions form, peat can begin to accumulate. Alkaline fluid within peat can react with the sediment below by dissolving quartz and concentrating clay by a process called gleying, which helps explain why underclay beds fine upward. Although the underclay at the top of the *Cincosaurus* beds is silty and thus weakly gleyed, the underclay below the Mary Lee coal is, in places, intensely gleyed and is mined in the Cordova area for ceramic applications.

New Castle Coal Bed

Characteristics. The New Castle coal is 0.30 m thick at the Union Chapel Mine and sharply overlies the *Cincosaurus* beds. Like the Mary Lee coal, the New Castle bed is bright-banded, lacks partings of shale or sandstone, and maintains uniform thickness. The New Castle bed has heating value (12,000 Btu/lb) and ash content (10-16%) similar to the Mary Lee bed, but sul-

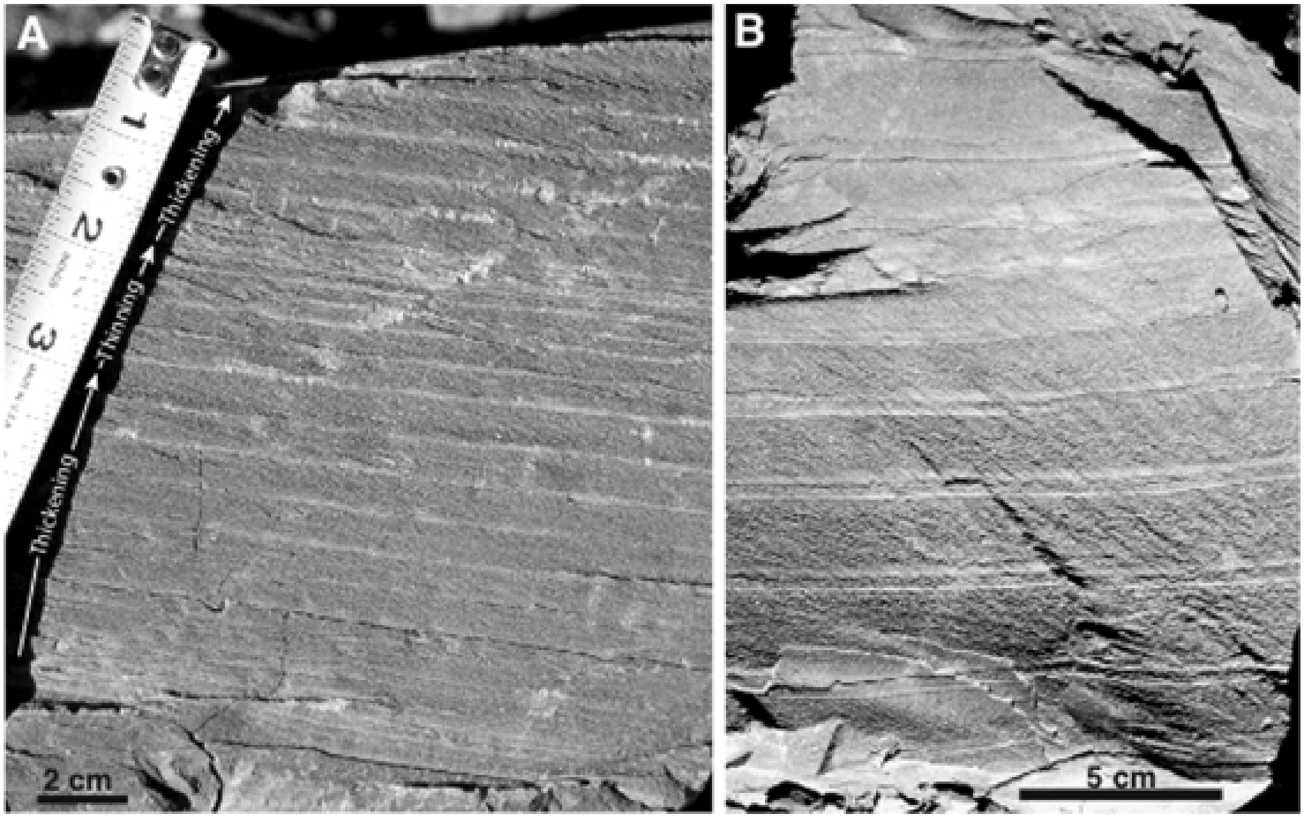

FIGURE 13. Graded siltstone-shale layers in the *Cincosaurus* beds at the Union Chapel Mine. Siltstone is lighter in color than shale. A, Progressive thickening and thinning of bedding. B, Paired thick and thin graded beds in oblique section.

fur content is markedly higher at 1.5 percent. In other mines in the Cordova area, sulfur content of the New Castle bed is as high as 5 percent (Tolson, 1986; Bragg et al., 1998).

The flora of the New Castle coal is similar to that in the Mary Lee coal, and coal balls from the New Castle bed in western Walker County, Alabama, provide a unique view of Pottsville floras (Winston and Phillips, 1991). Coal balls are limestone (calcium carbonate; $CaCO_3$) concretions that form in peat before deep burial and compaction, and the New Castle coal balls are significant because they are the oldest known from Pennsylvanian-age rocks in North America. Because coal balls form so early, they preserve the cell structure of ancient plants, and thus provide detailed information on the biology of ancient swamp forests. The New Castle coal balls preserve a diverse flora, with lycopods forming 82 percent of the biovolume, fern-like plants forming 4 percent, and a range of other plant types forming the remainder.

Interpretation. The New Castle coal signifies a return to lycopod-dominated peat swamp environments similar to those discussed earlier in the section on the Mary Lee coal. A lack of shaly partings plus ash content similar to that in the Mary Lee coal indicate that New Castle peat in the Union Chapel area accumulated in the interior of a low-lying swamp. The New Castle peat accumulation was thin compared to the Mary Lee bed and, based on the 10:1 peat-to-coal compaction ratio discussed earlier, original thickness of the New Castle peat was only about 3 m.

The relatively high sulfur content and local preservation of coal balls in the New Castle bed indicate that marine waters influenced coal quality. Coal balls are known exclusively from coal beds with marine or brackish roof strata, as is the case where the New Castle coal balls were discovered in northwestern Walker County, Alabama (Gastaldo et al., 1990; Winston and Phillips, 1991). Coal balls form as carbonate-saturated sea water infiltrates peat, and some of the carbonate may be derived directly from decaying plant material (Stopes and Watson, 1909; Scott and Rex, 1985). The high sulfur content of the New Castle bed in much of the the Cordova area provides evidence for bacterial sulfate reduction as marine water infiltrated peat. However, the sulfur content of the New Castle bed at the Union Chapel Mine is low for the Cordova area, and the key to determining why the sulfur content is low is to examine the roof strata.

New Castle Roof Shale

Characteristics. Above the New Castle coal bed is about 2.7 m of gray, silty shale with sparse, reddish siderite nodules (Fig. 11). The shale forms the top of the Mary

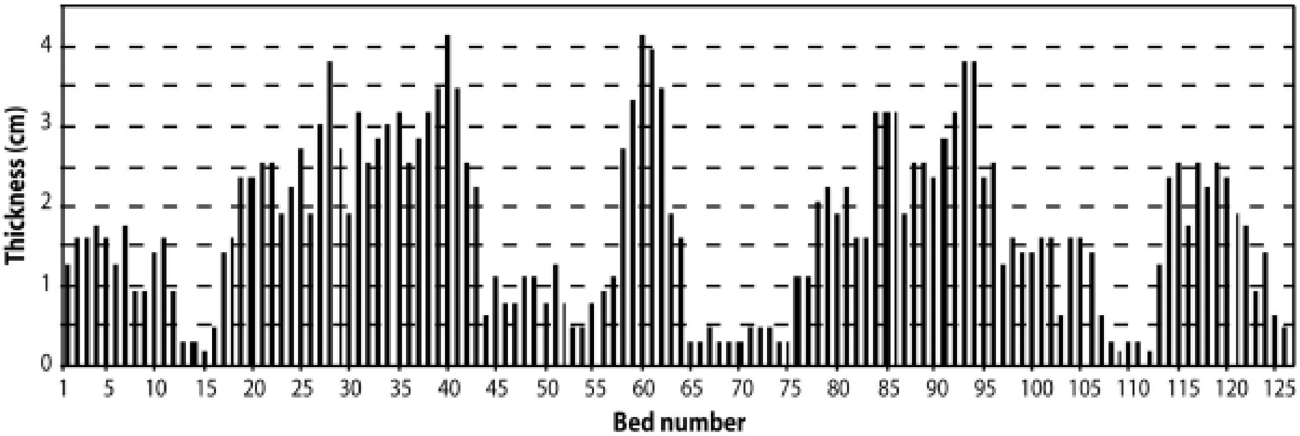

FIGURE 14. Bar chart showing variation of bedding thickness in the *Cincosaurus* beds at the Union Chapel Mine.

Lee coal zone and contains abundant plant fossils. This shale is typical of the roof strata above economic coal beds in the Appalachian region. The New Castle roof shale is poorly bedded compared to the *Cincosaurus* beds, and the presence of siderite nodules is another distinguishing feature. In contrast to the low-diversity flora of the *Cincosaurus* beds, the New Castle roof shale contains a rich and diverse plant assemblage. Indeed, most collectable plant fossils at the Union Chapel Mine come from this bed. Included in the assemblage are lycopods (*Lepidodendron, Lepidophloios*), sphenophytes (*Calamites, Sphenophyllum*), and several genera of fernlike foliage (*Neuropteris, Sphenopteris, Alethopteris,* and *Mariopteris*) (Dilcher et al., 2005).

Among the most distinctive features of the roof shale are erect lycopod and sphenophyte axes that are filled with shale. The lycopods can be distinguished from other erect plants because they have broad, flared bases. Careful examination of the shale indicates that the erect plants have root systems, including *Stigmaria*, preserved in at least two separate stratigraphic levels. Several layers contain abundant fern-like foliage as well as leaf and branch litter from lycopods. Similar stratigraphic relationships have been identified in plant-bearing intervals of the Mary Lee coal zone at other locations (Gastaldo et al., 1989; Demko and Gastaldo, 1992).

Interpretation. Abundant plants, including lycopods and sphenophytes fossilized in life position, indicate that the New Castle roof shale was deposited in a terrestrial setting. The diverse flora suggests analogy with the swamp forests that formed the Mary Lee and New Castle coal beds, and the flared bases of the lycopods are reminiscent of cypress trees in present-day low-lying wetlands of the southeastern United States. But the preservation of plant fossils in shale indicates that the New Castle roof shale represents a swamp that was prone to influxes of mud, perhaps by overbank flooding. These non-marine roof strata help explain why the sulfur content of the New Castle coal is below 2 percent at the Union Chapel Mine, because the mud protected the peat from direct infiltration of sea water. However, the elevated sulfur content of the New Castle coal relative to the Mary Lee coal suggests that some sea water and sulfur-reducing bacteria may have migrated laterally within the peat from nearby areas with marine roof strata.

The floral characteristics of different layers in terrestrial roof shale provide evidence of the ecological dynamics of swamp forests (Gastaldo et al., 1989; Demko and Gastaldo, 1992). Concentration of root systems and erect plant axes in distinct layers indicates that the roof shale does not represent a single swamp forest that grew for a sustained period, but represents multiple forests that were established at different times. Layers bearing fern-like foliage and leaf-branch litter just above the root layers may be the product of forest litter that accumulated during a time of relative stability. Major floods and associated influxes of mud, by comparison, are thought to have disturbed the swamp ecosystem, causing the plants to die and the forest canopy to drop to the surface. These events are thought to result in extensive layers of fossil plant litter and erect stumps.

Nodular Limestone

Characteristics. Above the roof shale is a bed of nodular (i.e., knobby) limestone that is about 15 cm thick (Fig. 11). The limestone is argillaceous, is dark gray, and contains abundant macerated fossils; it weathers with a dark red cast. Erect plant axes in the upper part of the New Castle roof shale are truncated at the base of the limestone. The lower contact of the limestone marks the top of the Mary Lee coal zone, and both contacts of the limestone are gradational and intensely burrowed. The nodular character of the limestone also is the product of burrowing.

Most fossil material in the nodular limestone has been broken, but some identifiable remains are present. The dominant types of fossils are productid brachiopods and bivalves. Gibson (1990) illustrated several fossils from this same bed in western Walker County, Alabama. Two species of strophomenid brachiopods were observed at the Union Chapel Mine, specifically *Antiquatonia portlockiana* (Norwood and Pratten) and *Desmoinesia muracatina* (Dunbar and Conrad). Also identified was the bivalve *Astartella concentrica* (Conrad). Gibson (1990) noted that marine faunas atop the Mary Lee coal zone in Walker County vary from

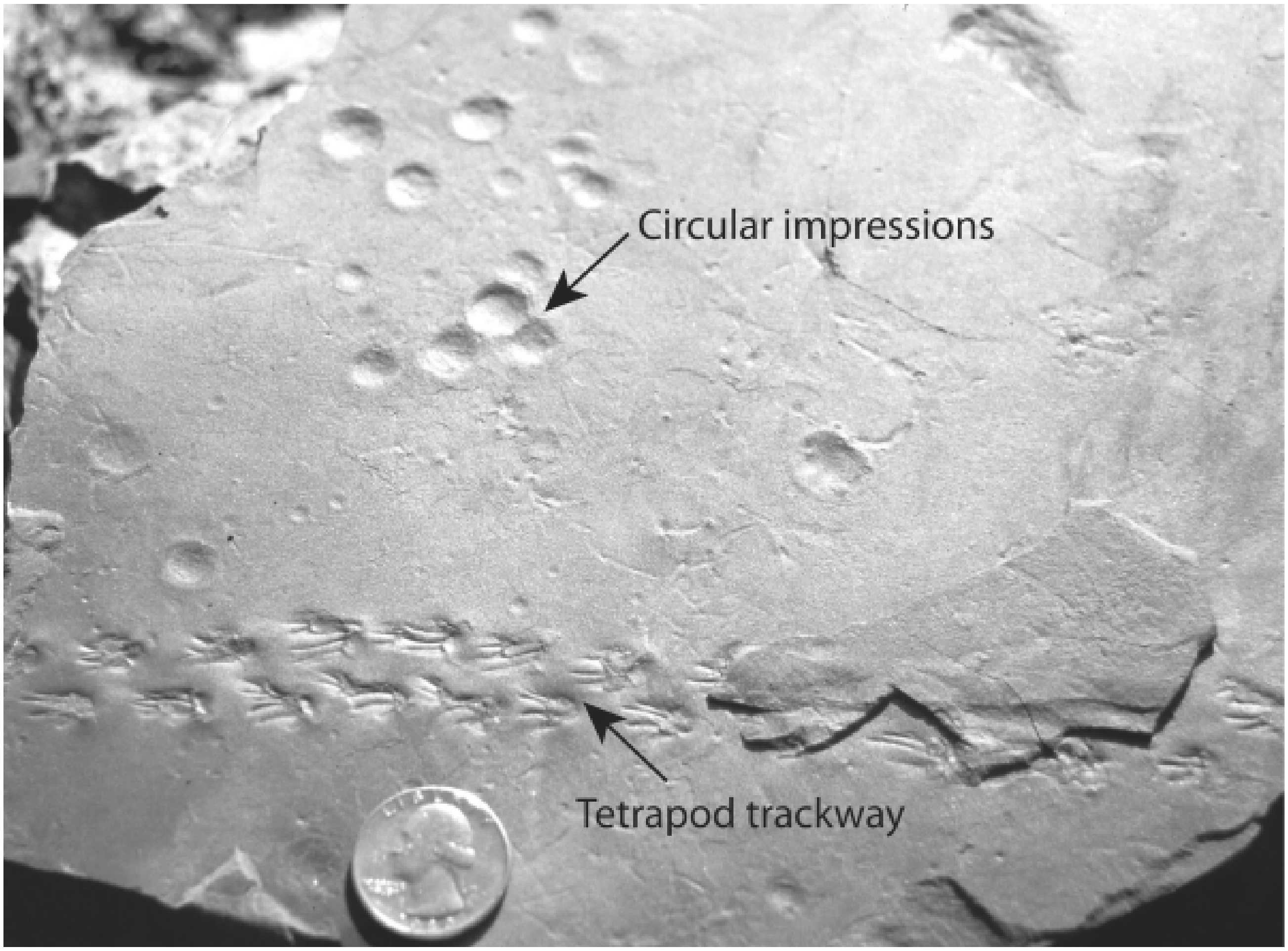

FIGURE 15. Small *trackway (Cincosaurus*) with crater-like gas-escape structures or raindrop impressions. Specimen collected by T. Prescott Atkinson.

outcrop to outcrop and in places include echinoderms, gastropods, and other types of molluscs.

Interpretation. The nodular limestone marks a change from terrestrial to marine sedimentation. Truncation of erect plants at the base of the limestone indicates that an episode of exposure or erosion predated marine deposition. Evidence of erosion is common at the base of the thin limy units atop the Pottsville coal zones, and this erosion is thought to be caused by current action (shoreface erosion) as the sea onlaps the coastal plain (Liu and Gastaldo, 1992). The predominance of productid brachiopods and bivalves in the limestone suggests that environmental conditions were stressed compared to other locations where echinoderms indicate more normal, open-marine sedimentation. The nodular texture of the limestone bed is the product of intense burrowing, which apparently caused maceration and disorientation of the shells.

Thin limestone units overlying transgressive surfaces of erosion are characteristic of condensed sections, which form when relative sea-level rise reaches a maximum rate (Vail, 1987; Posamentier and Vail, 1988) (Fig. 6). Condensed sections are thin but can represent large spans of geologic time because they form as mud and sand are held inshore by the transgressing sea. Indeed, the erosional surface below the limestone formed near the shoreline, whereas the top of the limestone represents the deepest water recorded in the Union Chapel section. Although the maximum water depth recorded in the Union Chapel section is unknown, absolute sea level changes during Early Pennsylvanian time are thought to have been greater than 40 m in magnitude (Maynard and Leeder, 1992).

Marine Shale and Sandstone

Characteristics. The upper part of the section in the Union Chapel Mine consists of gray shale that coarsens upward into thickly interbedded sandstone and shale (Fig. 11). This part of the section is the coarsening-upward shale-sandstone interval separating the Mary Lee and Gillespy coal zones (Fig. 2). The lower part of this interval consists of gray, silty shale with weak to moderate fissility. This shale is distinguished from older clay-rich beds in the Union Chapel Mine because it contains thin (~2 cm) bands of red-weathering siderite. No body fossils were recovered from this bed, but the shale is intensely burrowed, and careful examination reveals an abundance of horizontal tubular burrows ranging from

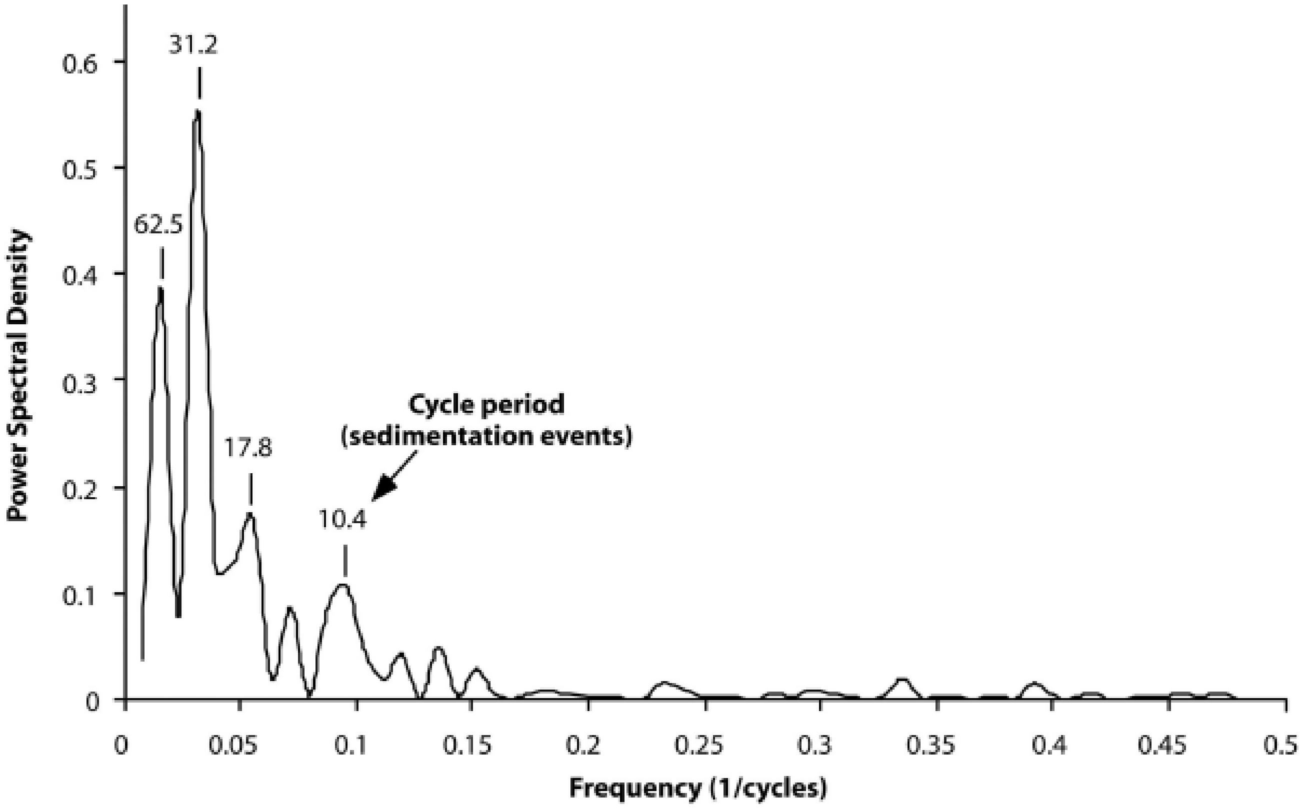

FIGURE 16. Results of Fourier transform analysis showing periodicity of bedding thickness cycles in the *Cincosaurus* beds (courtesy of E. P. Kvale).

about 1 to 3 mm in diameter.

About 12 m of interbedded gray shale and sandstone is accessible in the upper part of the highwall (Fig. 11). Shale is exposed in laminae to thick beds and is similar in character to that described above. Sandstone is very fine to fine grained, is light gray to medium gray, and forms laminae to thick beds. The sandstone beds have sharp bases and gradational tops. Abundant sole markings distinguish graded beds in the marine shale and sandstone from those in the *Cincosaurus* beds, and the sole marks mainly constitute prod marks, load casts, and horizontal burrow casts. Shale pebbles are locally present in the lower parts of the thick sandstone beds. Sedimentary structures within thin sandstone beds include horizontal laminae and current ripples. Within the thick sandstone beds, by comparison, sedimentary structure is dominated by horizontal laminae. Trace fossils are common in the interbedded shale and sandstone, and care must be taken to distinguish them from those in the *Cincosaurus* beds. The most common trace fossils in the marine shale and sandstone are horizontal tubular burrows. Other trace fossils include *Nereites* isp., which is a sinuous feeding trace of unknown affinity (Rindsberg, 1994).

The upper part of the highwall is inaccessible, but blocks in the mine talus indicate that the main rock types are dark gray, silty shale and medium gray, fine- to medium-grained sandstone. Shale and sandstone in the upper part of the section are thickly interbedded, and a variety of sedimentary structures are developed. In addition to current ripples and horizontal laminae like those identified near the top of the accessible section, thick sandstone beds contain crossbeds. Bedding becomes increasingly irregular and lensoid upward in section, and a broad, shallow channel filled with sandstone and shale is developed near the top of the highwall. Trace fossils, including abundant specimens of the horseshoe crab resting trace, *Arborichnus* isp. are common in the shale talus.

Interpretation: This interval is typical of major marine shale-sandstone units in the Pottsville Formation and was deposited in prodelta and delta-front environments (Figs. 6, 7). Prodelta areas are the muddy areas seaward of delta systems, and the lower, shale-dominated part of the interval apparently was deposited in this environment. Delta-front environments include sandy and muddy marine slopes near river mouths, and the thickly interbedded shale and sandstone near the top of the Union Chapel exposure are typical of delta-front deposits in the Pottsville Formation (e.g., Rheams and Benson, 1982; Pashin, 1994a). Trace fossils like *Nereites* confirm the marine origin of the mudstone (Seilacher, 1967; Rindsberg, 1994), although local conditions were not conducive to preservation of the shelly fauna that is common elsewhere at this stratigraphic level (Gibson, 1990).

Graded bedding indicates that sedimentation was episodic like in the *Cincosaurus* beds. However, graded sandstone layers in the marine shale and sandstone interval are irregularly distributed and thus represent rela-

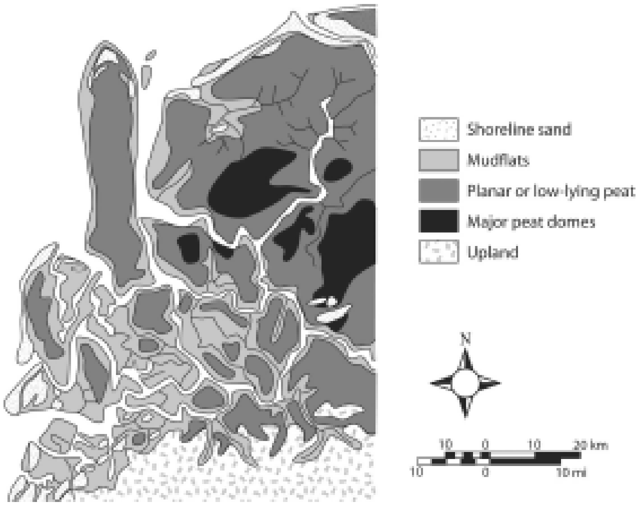

FIGURE 17. Possible modern analog for the Pottsville Formation, including the *Cincosaurus* beds, in the Rajang Delta of Indonesia (after Staub and Esterle, 1994).

tively rare depositional events. In delta-front environments, graded beds commonly are deposited as sediment-laden currents move downslope during episodes of high river discharge stimulated by heavy rainfall in the drainage basin (Martinsen, 1990). Graded beds also can be formed during local storm events in which sediment is eroded in proximal parts of the delta and is redeposited farther downslope. Crossbedding and channel fills near the top of the section are suggestive of delta-front environments close to the mouths of stream channels. In contrast to the episodic flows that formed graded beds lower in section, the flow of water was probably persistent close to the stream mouths. Crossbedding in the sandstone indicates that the flow was at times highly turbulent, and the channel fill is a testament to the erosive power in the shallow marine parts of delta systems.

SUMMARY AND CONCLUSIONS

The Union Chapel trace fossil assemblage is a fossil lagerstätte that can be considered in the context of the global, regional, and local events that shaped the world during Pennsylvanian time. The Union Chapel lagerstätte is in the Mary Lee coal zone of the Pottsville Formation, which is of Morrowan (Early Pennsylvanian) age and is an important source of coal and coalbed methane. The Early Pennsylvanian was a time of major tectonic and climatic changes associated with assembly of the supercontinent Pangaea, and the Pottsville Formation is a direct reflection of those changes.

The Black Warrior Basin formed at the juncture of the Appalachian and Ouachita orogenic belts, which provided most of the sediment that fills the basin. Pottsville strata were deposited in the humid tropics just south of the paleoequator and, at the same time, a major continental ice sheet existed in the south polar realm. Waxing and waning of the ice sheet resulted in lowering and raising of sea level that is expressed as marine-nonmarine depositional cyclicity in the Pottsville Formation. Climatic fluctuations controlling ice volume and sea level are thought to have been controlled by perturbations of the earth's orbit around the sun, specifically the long (0.4 Ma) and short (0.1 Ma) orbital eccentricity cycles. Most Pottsville depositional cycles were apparently deposited in the long eccentricity band, and stratigraphic variation within the cycles can be explained in part by sea level changes in the short eccentricity band.

Strata at the Union Chapel Mine are exposed from the upper part of the Mary Lee coal zone through the lower part of the Gillespy coal zone, and each bed exposed in the mine contains a different fossil assemblage reflecting different environments of deposition. The Mary Lee coal bed was the principal mining objective at the Union Chapel Mine and represents a widespread, low-lying peat swamp that was dominated by lycopods. The *Cincosaurus* beds overlie the Mary Lee coal and contain all the amphibian trackways recovered from the Union Chapel Mine, as well as a variety of other locomotion and resting trace fossils. The *Cincosaurus* beds evidently were deposited by tidal currents on a freshwater, estuarine mud flat that formed as the Mary Lee swamp was inundated. Rapid sedimentation in the *Cincosaurus* beds apparently reflects rapid compaction of Mary Lee peat, as well as rising sea level in the short eccentricity band. The trackways provide evidence for animals that were in transit, perhaps scouring the mudflat for food at low tide. At the top of the *Cincosaurus* beds is an underclay that provides evidence for widespread soil development, which may have been stimulated in response to a relative lowering of sea level.

As sea level rose again, a high water table formed, which was conducive to wetland development and gleying of the muddy soil horizon represented by the underclay. This episode culminated in renewed peat accumulation and formation of the New Castle coal. Roof strata above the New Castle bed record inundation of the swamp by marine water in much of Walker County, Alabama, but roof strata at the Union Chapel Mine indicate that persistent terrestrial wetland sedimentation protected the New Castle peat from degradation by sulfur-reducing bacteria. These strata preserve standing forests at multiple stratigraphic levels and contain diverse and well-preserved compression floras.

Erect plant fossils in the New Castle roof shale are truncated below a nodular limestone bed, which records a major (i.e., long eccentricity) marine flooding event that marks the top of the Mary Lee coal zone. The limestone contains a condensed brachiopod-mollusc assemblage that formed during the most rapid phase of sea-level rise. The upper part of the Union Chapel highwall contains a coarsening-upward shale-sandstone interval that was deposited in prodelta and delta-front environments during a major highstand of relative sea level. This event set the stage for deposition of younger Pottsville strata in which yet other Fossil-Lagerstätten may await discovery.

ACKNOWLEDGMENTS

This manuscript was reviewed by M. A. Gibson and J. R. Lowery, who made many useful suggestions that improved the quality of this contribution. E. P. Kvale of

the Indiana Geological Survey kindly performed a Fourier transform analysis of bedding in the *Cincosaurus* beds using the maximum entropy method.

REFERENCES

Aldrich, T. H., Sr. and Jones, W. B., 1930, Footprints from the coal measures of Alabama: Alabama Museum of Natural History, Museum Paper 9, 64 p.

Anderson, J. A. R., 1964, Structure and development of the peat swamps of Sarawak and Brunei: Journal of Tropical Geography, v. 18, p. 7-16.

Archer, A. W., 1991, Modeling of tidal rhythmites using modern tidal periodicities and implications for short-term sedimentation rates: Kansas Geological Survey Bulletin, no. 233, p. 185-194.

Berger, A. L., and Loutre, M. F., 1991, Insolation values for the climate of the last 10 million years: Quaternary Science Review, v. 10, p. 297-317.

Bragg, L. J., Oman, J. K., Tewalt, S. J., Oman, C. L., Rega, N. H., Washington, P. M., and Finkelman, R. B., 1998, U.S. Geological Survey coal quality database (COALQUAL), version 2.0: U.S. Geological Survey Open-File Report 97-134 (CD-ROM).

Buta, R. J., Kopaska-Merkel, D. C., Rindsberg, A. K., and Martin, A. J., 2005, Atlas of Union Chapel Mine invertebrate trackways and other traces; in Buta, R. J., Rindsberg, A. K. and Kopaska-Merkel, D. C., eds., Pennsylvanian Footprints in the Black Warrior Basin of Alabama: Alabama Paleontological Society Monograph no. 1, p. 277-337.

Butts, C., 1910, Description of the Birmingham Quadrangle, Alabama: U.S. Geological Survey Geologic Atlas of the United States, Folio 175, 24 p.

Butts, C., 1926, The Paleozoic rocks; in Adams, G. I., Butts, C., Stephenson, L. W. and Cooke, C. W., Geology of Alabama: Alabama Geological Survey Special Report 14, p. 41-230.

Caputo, M. V. and Crowell, J. C., 1985, Migration of glacial centers across Gondwana during Paleozoic Era: Geological Society of America Bulletin, v. 96, p. 1020-1036.

Carroll, R. E., 1997, Alabama coal data for 1994: Alabama Geological Survey Information Series 58P, 132 p.

Carroll, R. E., Pashin, J. C. and Kugler, R. L., 1995, Burial history and source-rock characteristics of Upper Devonian through Pennsylvanian strata, Black Warrior basin, Alabama: Alabama Geological Survey Circular 187, 29 p.

Casagrande, D. J., 1987, Sulphur in peat and coal; in Scott, A. C., ed., Coal and coal-bearing strata: recent advances: Geological Society of London Special Publication no. 32, p. 87-105.

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

Cobb, J. C., Chesnut, D. R., Hester, N. C. and Hower, J. C., 1981, Coal and coal-bearing rocks of eastern Kentucky. Lexington, Kentucky, Kentucky Geological Survey, Annual Geological Society of America Coal Division Field Trip Guidebook, 169 p.

Cohen, A. D., 1974, Petrography and paleoecology of Holocene peats from the Okefenokeee swamp-marsh complex of Georgia: Journal of Sedimentary Petrology, v. 44, p. 716-726.

Culbertson, W. C., 1964, Geology and coal resources of the coal-bearing rocks of Alabama: U.S. Geological Survey Bulletin 1182-B, 79 p.

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

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

Eble, C. F., Gastaldo, R. A., Demko, T. M., and Liu, Y., 1994, Coal compositional changes along a swamp interior to swamp margin transect in the Mary Lee Coal bed, Warrior Basin, Alabama, U.S.A: International Journal of Coal Geology, v. 26, p. 43-62.

Eble, C. F. and Gillespie, W. H., 1989, Palynology of selected coal beds from the central and southern Appalachian basin: correlation and stratigraphic implications: Washington, D.C., 28th International Geological Congress, Guidebook T352, p. 61-66.

Eble, C. F., Gillespie, W. H. and Henry, T. W., 1991, Palynology, paleobotany, and invertebrate paleontology of Pennsylvanian coal beds and associated strata in the Warrior and Cahaba coal fields; in Thomas, W.A., and Osborne, W. E., eds., Mississippian-Pennsylvanian tectonic history of the Cahaba synclinorium: Alabama Geological Society Guidebook, 28th Annual Field Trip, p. 119-132.

Elder, C. H. and Deul, M., 1974, Degasification of the Mary Lee coalbed near Oak Grove, Jefferson County, Alabama, by vertical borehole in advance of mining: U.S. Bureau of Mines Report of Investigations 7968, 21 p.

Ferm, J. C., Ehrlich, R. and Neathery, T. L., 1967, A field guide to Carboniferous detrital rocks in northern Alabama: Geological Society of America, 1967 Coal Division Field Trip Guidebook, 101 p.

Ferm, J. C. and Weisenfluh, G. A., 1989, Evolution of some depositional models in Late Carboniferous rocks of the Appalachian coal fields: International Journal of Coal Geology, v. 12, p. 259-292.

Frakes, L. A., Francis, J. E. and Syktus, J. I., 1992, Climate modes of the Phanerozoic. Cambridge, Cambridge Press, 274 p.

Galloway, W. E., 1989, Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units: American Association of Petroleum Geologists Bulletin, v. 73, p. 125-142.

Gardner, T. W., Williams, E. G. and Holbrook, P. W., 1988, Pedogenesis of some Pennsylvanian underclays: ground-water, topographic, and tectonic controls: Geological Society of America, Special Paper, no. 216, p. 81-101.

Gastaldo, R. A., Demko, T. M., and Liu, Y. eds., 1990, Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Alabama Geological Survey Guidebook Series VI, 139 p.

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

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

Gentzis, T., 2000, Subsurface sequestration of carbon dioxideùan overview from an Alberta (Canada) perspective: International Journal of Coal Geology, v. 43, p. 287-305.

Gibson, M. A., 1990, Common macroinvertebrates associated with the Mary Lee coal zone (Pennsylvanian, upper Pottsville Formation), northern Alabama; in Gastaldo, R. A., Demko, T. M., and Liu, Y., eds., Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Alabama Geological Survey Guidebook Series VI, p. 97-104.

Gillespie, W. H., Clendening, J. A. and Pfefferkorn, H. W., 1978, Plant fossils of West Virginia: West Virginia Geological and Economic Survey Educational Series, ED-3A, 172 p.

Heckel, P. H., 1986, Sea-level curve for Pennsylvanian eustatic transgressive-regressive depositional cycles along midcontinent outcrop belt, North America: Geology, v. 14, p. 330-334.

Heckel, P. H., 1994, Evaluation of evidence for glacio-eustatic control over marine Pennsylvanian cyclothems in North America and consideration of possible tectonic effects; in Dennison, J. M., and Ettensohn, F. R. eds., Tectonic and Eustatic Controls on Sedimentary Cycles: Society for sedimentology, Concepts in Sedimentology and Paleontology, no. 4, p. 89-105.

Hewitt, J. L., 1984, Geologic overview, coal, and coal bed methane resources of the Warrior basin — Alabama and Mississippi; in Rightmire, C. T., Eddy, G. E., and Kirr, J. N., eds., Coal bed methane resources of the United States: American Association of Petroleum Geologists, Studies in Geology, no. 17, p. 73-104.

Hobday, D. K., 1974, Beach and barrier island facies in the Upper Carboniferous of northern Alabama: Geological Society of America Special Paper, no. 148, p. 209-224.

Horne, J. C., 1979, The effects of Carboniferous shoreline geometry on paleocurrent distribution; in Ferm, J. C. and Horne, J. C., eds., Carboniferous depositional environments in the Appalachian region: Carolina Coal Group, University of South Carolina, Columbia, South Carolina, p. 509-516.

Horsey, C. A., 1981, Depositional environments of the Pennsylvanian Pottsville Formation in the Black Warrior basin of Alabama: Journal of Sedimentary Petrology, v. 51, p. 799-806.

Imbrie, J., 1985, A theoretical framework for the Pleistocene ice ages: Journal of the Geological Society of London, v. 142, p. 417-432.

Imbrie, J. and Imbrie, J. Z., 1980, Modeling the climatic response to orbital variations: Science, v. 207, p. 943-953.

Klein, G. deV., 1977, Clastic Tidal Facies: Dordrecht, D. Reidel Publishing, 119 p.

Kvale, E. P., Archer, A. W. and Johnson, H. R., 1989, Daily, monthly, and yearly tidal cycles within laminated siltstones of the Mansfield Formation (Pennsylvanian) of Indiana: Geology, v. 17, p. 365-368.

Kvale, E. P. and Mastalerz, M., 1998, Evidence of ancient freshwater tidal deposits; in Alexander, C. R., Davis, R. A., and Henry, V. J., eds., Tidalites: Processes and Products: Society for Sedimentology Special Publication, no. 61, p. 95-107.

Lahee, F. H., 1961, Field geology (6th edition): New York, McGraw Hill, 926 p.

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

Mack, G. H., James, W. C. and Monger, H. C., 1993, Classification of paleosols: Geological Society of America Bulletin, v. 105, p. 129-136.

Martinsen, O. J., 1990, Fluvial, inertia-dominated deltaic deposition in the Namurian (Carboniferous) of northern England: Sedimentology, v. 37, p. 1099-1113.

Maynard, J. R. and Leeder, M. R., 1992, On the periodicity and magnitude of Late Carboniferous glacio-eustatic sea-level changes: Journal of the Geological Society of London, v. 149, p. 303-311.

McCabe, P. J., 1984, Depositional environments of coal and coal-bearing strata; in Rahmani, R. A., and Flores, R. M., eds., Sedimentology of coal and coal-bearing strata: International Association of Sedimentologists Special Publication, no. 7, p. 13-42

McCalley, H., 1886, On the Warrior coal field: Alabama Geological Survey Special Report 1, 571 p.

McCalley, H., 1900, Report on the Warrior coal basin: Alabama Geological Survey Special Report 10, 327 p.

McFall, K. S., Wicks, D. E., and Kuuskraa, V. A., 1986, A geological assessment of natural gas from coal seams in the Warrior basin, Alabama — topical report (September 1985-September 1986). Lewin and Associates, Inc., Washington, D. C., Gas Research Institute contract no. 5084-214-1066, 80 p.

Mellen, F. F., 1947, Black Warrior basin, Alabama and Mississippi: American Association of Petroleum Geologists Bulletin, v. 31, p. 1801-1816.

Metzger, W. J., 1965, Pennsylvanian stratigraphy of the Warrior basin, Alabama: Alabama Geological Survey Circular 30, 80 p.

Nadon, G. C., 1998, Magnitude and timing of peat-to-coal compaction: Geology, v. 26, p. 727-730.

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

Pashin, J. C., 1994b, Flexurally influenced eustatic cycles in the Pottsville Formation (Lower Pennsylvanian), Black Warrior basin, Alabama; in Dennison, J. M. and Ettensohn, F. R. eds., Tectonic and Eustatic Controls on Sedimentary Cycles: Society for Sedimentology, Concepts in Sedimentology and Paleontology, no. 4, p. 89-105.

Pashin, J. C., 1994c, Coal-body geometry and synsedimentary detachment folding in Oak Grove coalbed-methane field, Black Warrior basin, Alabama: American Association of Petroleum Geologists Bulletin, v. 78, p. 960-980.

Pashin, J. C., 1998, Stratigraphy and structure of coalbed methane reservoirs in the United States: an overview: International Journal of Coal Geology, v. 35, p. 207-238.

Pashin J. C. and Carroll, R. E., eds., 1998, Geology of the Cahaba coalfield: Alabama Geological Society, 36th Annual Field Trip Guidebook, 98 p.

Pashin, J. C., Carroll, R. E., Barnett, R. L. and Beg, M. A., 1995, Geology and coal resources of the Cahaba coal field: Alabama Geological Survey Bulletin 163, 49 p.

Pashin, J. C., Carroll, R. E., Groshong, R. H., Jr., Raymond, D. E., McIntyre, M. and Payton, W. J., 2003, Geologic screening criteria for sequestration of CO_2 in coal: quantifying potential of the Black Warrior coalbed methane fairway, Alabama: Annual Technical Progress Report, U.S. Department of Energy, National Technology Laboratory, contract DE-FC-00NT40927, 190 p.

Pashin, J. C., Groshong, R. H., Jr. and Carroll, R. E., 2001, Carbon sequestration potential of coalbed methane reservoirs in the Black Warrior basin: a preliminary look. Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 2001 International Coalbed Methane Symposium, Proceedings, p. 51-62.

Pashin, J. C. and Hinkle, F., 1997, Coal bed methane in Alabama. Alabama Geological Survey Circular 192, 71 p.

Pashin, J. C., Ward, W. E., II, Winston, R. B., Chandler, R. V., Bolin, D. E., Richter, K. E., Osborne, W. E. and Sarnecki, J., C. 1991, Regional analysis of the Black Creek-Cobb coalbed-methane target interval, Black Warrior basin, Alabama: Alabama Geological Survey Bulletin 145, 127 p.

Posamentier, H. W. and Vail, P. R., 1988, Eustatic controls on clastic deposition, II. Sequence and systems tract models: Society of Economic Paleontologists and Mineralogists Special Publication, no. 42, p. 125-154.

Reichle, D., Houghton, J., Kane, B. and Ekmann, J., 1999, Carbon sequestration: State of the science. U.S. Department of Energy, Offices of Science and Fossil Energy, unpaginated PDF document.

Reineck, H.-E., 1955, Marken, Spuren, und Fährten in den Waderner Schichten (ro) bei Martinstein/Nahe: Neues Jahrbuch fur Geologie und Paläontologie, Abhandlungen, v. 101, p. 75-90.

Renton, J. J. and Cecil, C. B., 1979, The origin of mineral matter in coal; in Donaldson, A. C., Presley, M. W., and Renton, J.

J., eds., Carboniferous Coal Guidebook, v. 1: West Virginia Geologic and Economic Survey Bulletin 37-1, p. 206-233.
Rheams, L. J. and Benson, D. J., 1982, Depositional setting of the Pottsville Formation in the Black Warrior basin: Alabama Geological Society 19th Annual Field Trip Guidebook, 94 p.
Rial, J. A., 1999, Pacemaking the ice ages by frequency modulation of Earth's orbital eccentricity: Science, v. 285, p. 564-568.
Rindsberg, A. K., 1990, Freshwater to marine trace fossils of the Mary Lee coal zone and overlying strata (Westphalian A), Pottsville Formation of northern Alabama; in Gastaldo, R. A., Demko, T. M., and Liu, Y., eds., Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Alabama Geological Survey Guidebook Series VI, p. 82-95.
Rindsberg, A. K., 1994, Ichnology of the Upper Mississippian Hartselle Sandstone of Alabama, with notes on other Carboniferous formations: Alabama Geological Survey Bulletin 158, 107 p.
Scotese, C. R., 1990, Atlas of Phanerozoic plate tectonic reconstructions: International Lithosphere Program (IUGG-IUGS), Paleomap Project Technical Report 10-90-1, 54 p.
Scotese, C. R., Golonka, J., and Ross, M .I., 1994, Phanerozoic paleogeographic and paleoclimatic modeling maps; in Embry, A. F., Beauchamp, B. and Glass, D. J., eds., Pangea, global environments and resources: Canadian Society of Petroleum Geologists, Memoir, no. 17, p. 1-47.
Scott, A. C. and Rex, G., 1985, The formation and significance of Carboniferous coal balls: Philosophical Transactions of the Royal Society of London, v. 311B, p. 123-137.
Seilacher, A., 1967, Bathymetry of trace fossils: Marine Geology, v. 5, p. 413-428.
Seilacher, A., 1990, Taphonomy of Fossil-Lagerstätten; in Briggs, D. E. G. and Crowther, P. R., eds., Palaeobiology: a synthesis. London, Blackwell, p. 266-270.
Sestak, H. M., 1984, Stratigraphy and depositional environments of the Pennsylvanian Pottsville Formation in the Black Warrior basin, Alabama and Mississippi: Tuscaloosa, University of Alabama, M. S. Thesis, 184 p.
Shrock, R. R., 1948, Sequence in layered rocks. New York, McGraw-Hill, 507 p.
Spears, D. A., 1987, Mineral matter in coals, with special reference to the Pennine Coalfields; in Scott, A. C., (ed.), Coal and coal-bearing strata: recent advances: Geological Society of London Special Publication, no. 32, p. 171-185.
Staub, J. R. and Esterle, J. S., 1994, Peat-accumulating depositional systems of Sarawak, eastern Malaysia: Sedimentary Geology, v. 89, p. 91-106.
Stopes, M. C. and Watson, D. M. S., 1909, On the present distribution and origin of the calcareous concretions in coal seams, known as coal balls: Philosophical Transactions of the Royal Society of London, ser. B, v. 200, p. 167-218.
Telle, W. R., Thompson, D. A., Lottman, L. K. and Malone, P. G., 1987, Preliminary burial-thermal history investigations of the Black Warrior basin: implications for coal bed methane and conventional hydrocarbon development: Tuscaloosa, University of Alabama, College of Continuing Studies, 1987 Coalbed Methane Symposium Proceedings, p. 37-50.
Thomas, W. A., 1974, Converging clastic wedges in the Mississippian of Alabama: Geological Society of America, Special Paper, no. 148, p. 187-207.
Thomas, W. A., 1976, Evolution of the Appalachian-Ouachita continental margin: Journal of Geology, v. 84, p. 323-342.
Thomas, W. A., 1977, Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: American Journal of Science, v. 277, p. 1233-1278.
Thomas, W. A., 1985, The Appalachian-Ouachita connection: Paleozoic orogenic belt at the southern margin of North America: Annual Reviews of Earth and Planetary Sciences, v. 13, p. 175-199.
Thomas, W. A., 1988, The Black Warrior Basin; in Sloss, L. L., ed., Sedimentary cover — North American craton: Geological Society of America, The Geology of North America, v. D-2, p. 471-492.
Thomas, W. A. and Womack, S. H., 1983, Coal stratigraphy of the deeper part of the Black Warrior Basin in Alabama: Gulf Coast Association of Geological Societies, Transactions, v. 33, p. 439-446.
Tolson, J. S., 1986, Coal occurrence and general geology in the Cordova 7.5-Minute Quadrangle, Walker County, Alabama: Alabama Geological Survey Open File Report, 15 p.
Vail, P. R., 1987, Seismic stratigraphy interpretation procedure: American Association of Petroleum Geologists Studies in Geology, no. 27 (1), p. 1-10.
van Straaten, L. J. M. U., 1954, Sedimentology of Recent tidal flat deposits and the Psammites du Condroz (Devonian): Geologie en Mijnbouw, v. 15, p. 1-11.
Wanless, H. R. and Shepard, F. P., 1936, Sea level and climatic changes related to late Paleozoic cycles: Geological Society of America Bulletin, v. 47, p. 1177-1206.
Ward, W. E., II, 1984, Reserve base of bituminous coal and lignite in Alabama: Alabama Geological Survey Circular 118, 102 p.
Weller, S., 1930, Cyclic sedimentation of the Pennsylvanian Period and its significance: Journal of Geology, v. 38, p. 97-135.
Williams, E. G. and Keith, M. L., 1963, Relationship between sulfur in coals and the occurrence of marine roof beds: Economic Geology, v. 58, p. 720-729.
Winston, R. B., 1990, Coal-paleobotany of the Mary Lee coal bed of the Pennsylvanian Pottsville Formation near Carbon Hill, Walker County, Alabama; in Gastaldo, R. A., Demko, T. M. and Liu, Y., eds., Carboniferous coastal environments and paleocommunities of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Alabama Geological Survey Guidebook Series VI, p. 55-64.
Winston, R. B. and Phillips, T. L., 1991, A structurally preserved, Lower Pennsylvanian flora from the New Castle coal bed of Alabama: Alabama Geological Survey Circular 157, 21 p.

AUTHOR'S E-MAIL ADDRESS

jpashin@gsa.state.al.us