Carboniferous Geology and Biostratigraphy of the Appalachian Basin

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Carboniferous of the Appalachian and Black Warrior Basins

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Foreward

Between 1983 and 1996, the Subcommission on Carboniferous Stratigraphy (a division of the International Commission on Stratigraphy, under the auspices of the International Union of Geological Sciences) sponsored publication of three volumes entitled "The Carboniferous of the World." These volumes were a summary of the biostratigraphy of the Carboniferous on all of the continents except for North America and central to western Europe. In 1997, the call went out to North American and European geologists to begin compilation of Carboniferous (Mississippian and Pennsylvanian) stratigraphy and paleontology of those regions to produce the last two planned volumes of "Carboniferous of the World." These regions include many of the world's major coal basins. Don Chesnut of the Kentucky Geological Survey was asked to solicit authors for a series of papers concerning the Carboniferous of the Appalachian Basin to contribute to the North American volume. Don arranged for regional experts to submit papers that summarized the current understanding of the lithostratigraphy and biostratigraphy of the basin. In all, 12 papers were submitted, peer reviewed, edited, and compiled into a chapter on the basin. Unfortunately, the larger compilation that included other parts of North America suffered delays. In the following years, Don retired from the Kentucky Geological Survey, and the North American volume remained unpublished. Rather than allowing the papers that had been submitted for the Appalachian Basin to languish unpublished, or publishing the papers in separate journals or other venues, the authors of the papers for the greater Appalachian Basin chose to publish their papers together through the Kentucky Geological Survey. The volume's authors updated their manuscripts and they are presented here in their entirety. Similarly, a summary of the Midcontinent and Illinois Basin in the central United States is planned to be published by the Kansas Geological Survey. We hope volumes on additional basins will be published in the near future.

Sincerely,
Stephen Greb

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1: Introduction

Donald R. Chesnut Jr. and Stephen F. Greb

In the United States, the Carboniferous is divided into the Mississippian and Pennsylvanian Systems. In much of the rest of the world, the terms Lower and Upper Carboniferous were used rather than Mississippian and Pennsylvanian. In 1999, however, the International Commission on Stratigraphy and the International Union of Geological Sciences formalized the terms Mississippian and Pennsylvanian as subsystems of the Carboniferous across the world. In 2003, series boundaries for Lower, Middle, and Upper Mississippian and Pennsylvanian were ratified. These boundaries coincide with western and eastern European named stages, which were formalized in 2004 as global stage names (Heckel and Clayton, 2006). To facilitate correlations of the rock strata of the Appalachian Basin to strata in other basins and the new global stages, the existing lithostratigraphy (rock layering) of the basin and biostratigraphy (fossils and fossil successions) is summarized herein.

The Appalachian Basin and contiguous Black Warrior Basin are Carboniferous basins located in the eastern United States (Fig. 1.1). Because coal studies of the Black Warrior Basin have informally grouped resources into the Appalachian Basin, for the purposes of this volume the Black Warrior Basin is considered part of the greater Appalachian Basin. In the greater Appalachian Basin, lithostratigraphy is generally used to correlate rock units across and between states. For Mississippian strata (dominated by marine carbonates), various marine fossil and fossil successions (known stratigraphic ranges of fossil occurrences) are used to test correlations between states and to correlate Appalachian Mississippian strata to other basins. For Pennsylvanian strata (dominated by terrestrial clastic rocks and coals), terrestrial fossils (plant spores and megafossils) are the principal tool for biostratigraphic correlation between states and into other basins. Internationally, correlation of the Mississippian Series (Upper, Middle, Lower) is based on marine conodonts and foraminifera. The Pennsylvanian Series (Upper, Middle, Lower) is correlated based on marine conodonts, fusulinids, and ammonoids (Gradstein and others, 2004). In the Upper Mississippian and much of the Pennsylvanian of the Appalachian Basin, however, conodonts, fusulinids, and ammonoids are rare. Hence, biostratigraphic correlations of series, stages, and rock unit groups, formations, members, and beds from the Appalachian Basin into other U.S. basins or European and global basins are based mostly on paleoflora (spores and megafossils), supported by more limited marine fauna.

Regional Stratigraphy and Correlations

The combined Appalachian/Black Warrior Basin, as preserved today, is 1,300 km at its longest and 320 km at its widest dimension. Moreover, Mississippian (Lower Carboniferous) strata overlie parts of the Cincinnati Arch along the western margin of the basin, to form a continuous outcrop with the Carboniferous strata of the Illinois Basin (Fig. 1.1). This extensive, unbroken exposure between the Appalachian, Black Warrior, and Illinois Basins is one of the largest continuous outcrops of Carboniferous strata in the world. Figures 1.2 through 1.5 are cross sections of Carboniferous strata across the greater Appalachian Basin. The datum for all five cross sections is the Mississippian-Pennsylvanian contact. Important sources of information on the general stratigraphy of the basins are McKee and Crosby (1975), Arkle and others (1979), Bicker (1979), Collins (1979), Craig and Connor (1979), Edmunds and others (1979), Milici and others (1979), Rice and others (1979), Smith (1979), Thomas (1979), and Thomas and Cramer (1979).

General Geology

The Appalachian and Black Warrior Basins are foreland basins associated with the Appalachian and Ouachita orogens, respectively. The tectonic causes, evolution, and chronology of basin formation are a matter of debate, but most agree with the following. The clastic wedges of the lower part of the Mississippian reflect the waning stages of the Acadian Orogeny (mostly Devonian). Extensive carbonates of the middle part of the Mississippian reflect tectonically passive conditions. The siliciclastics of the later Mississippian and the entire Pennsylvanian represent increasingly active tectonism along the Alleghanian orogen (mostly Pennsylvanian and Permian). Basin formation during this period is largely attributed to tectonic loading and related mechanisms. Models for tectonic evolution of these basins, albeit sometimes contradictory, are discussed in Thomas (1977, 1988), Tankard (1986), Hatcher and others (1988), Milici and deWitt (1988), Osberg and others (1988), Ettensohn and Chesnut (1989), and Chesnut (1991).

This Volume

The following papers provide a more detailed description of Carboniferous basin development, stratigraphic framework, and biostratigraphy of the greater Appalachian Basin. The first three papers are overviews

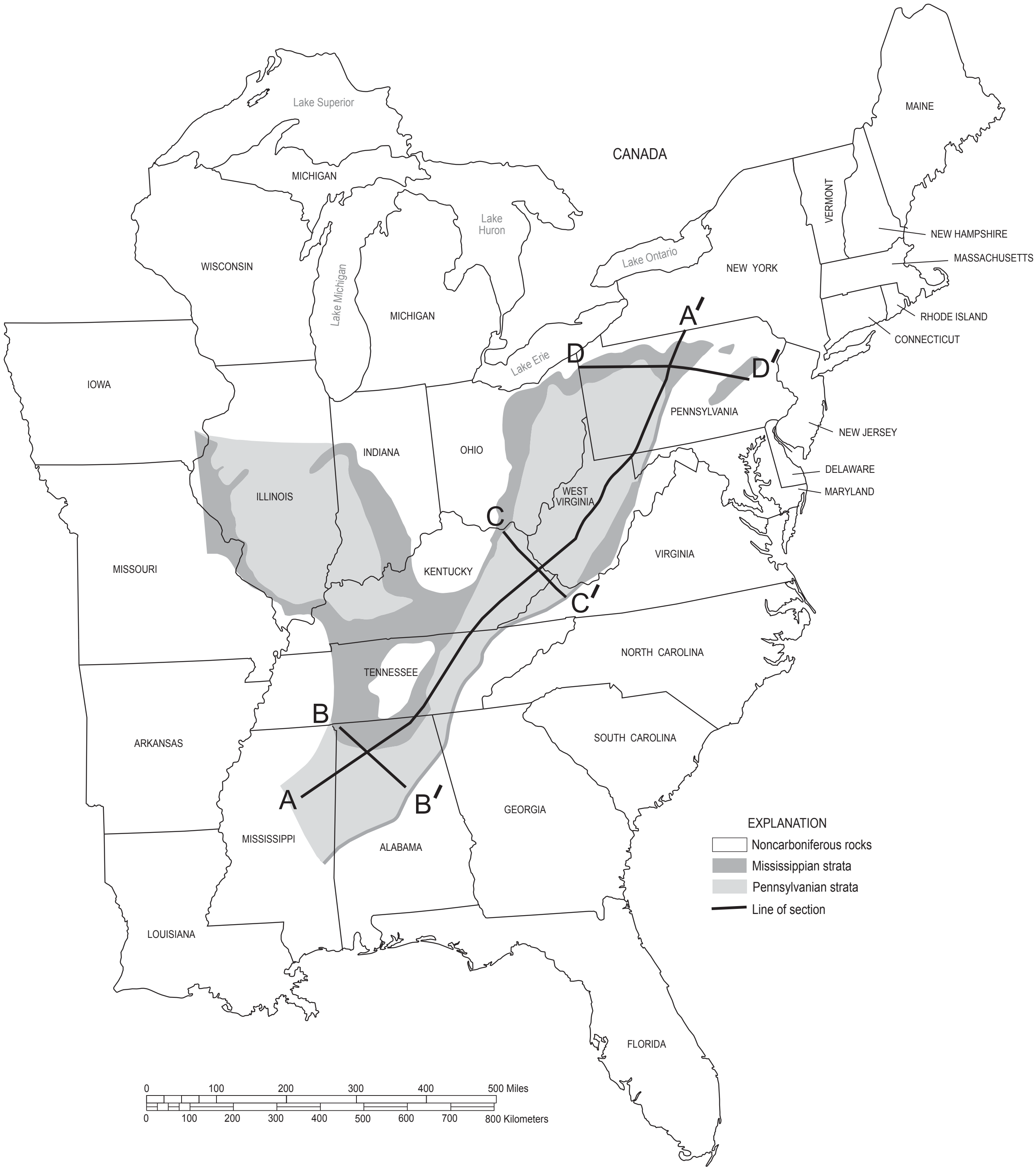

Figure 1.1. Carboniferous strata of the Appalachian, Black Warrior, and part of the Illinois Basins to the west. Locations of cross sections in the Appalachian (sections A–A′, C–C′, and D–D′) and Black Warrior (sections B–B′ and southern part of A–A′) Basins are indicated on the map.

of the stratigraphy and general geologic history of Carboniferous stratigraphy and sedimentation in the greater Appalachian Basin. The eight papers that follow describe key fossils and fossil successions that are used to correlate the stratigraphy of the greater Appalachian Basin between states comprising the greater basin, and other basins worldwide.

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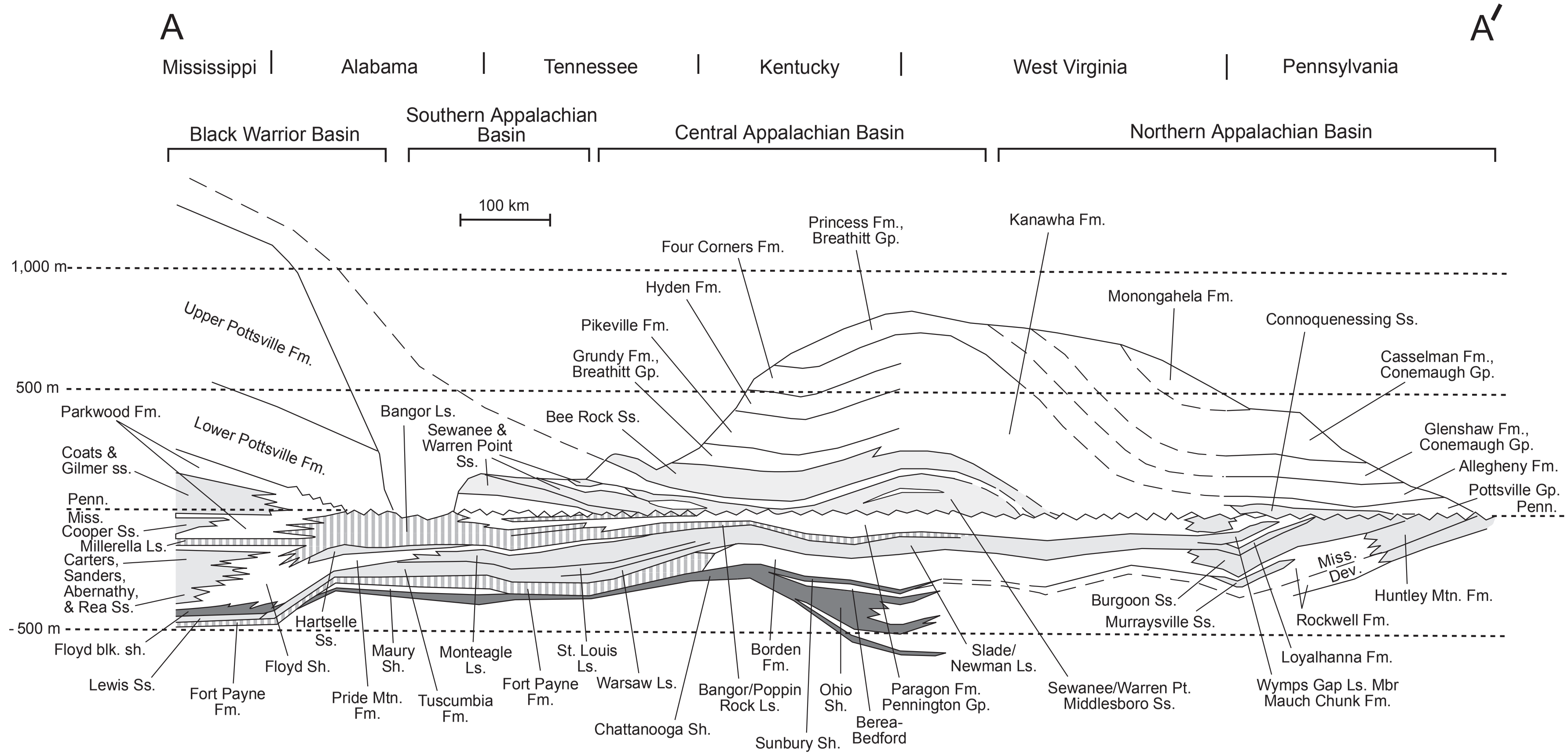

Figure 1.2. Cross section A–A′ of the Appalachian and Black Warrior Basins. See Figure 1.1 for orientation. Datum is the Mississippian-Pennsylvanian contact.

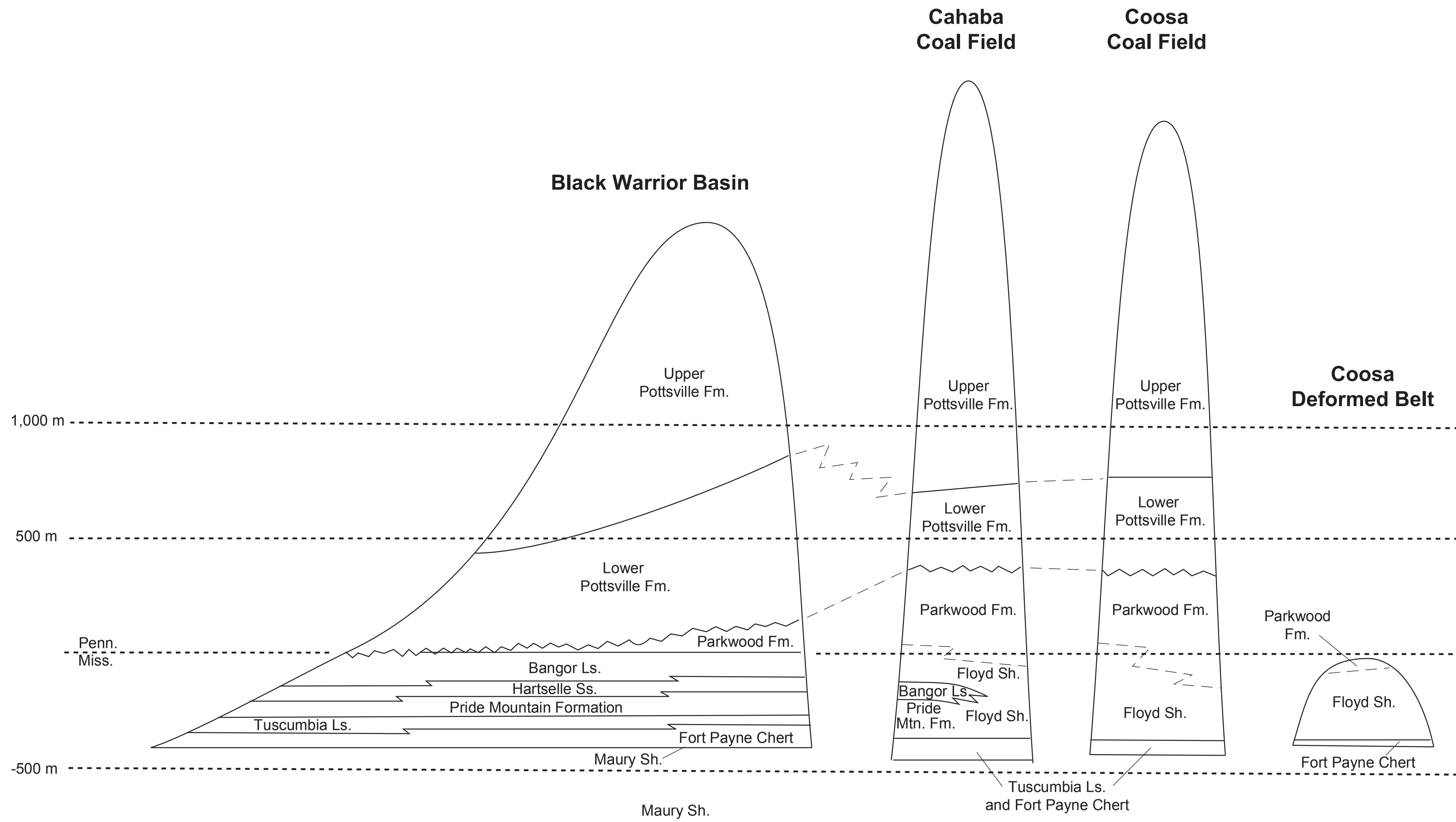

Figure 1.3. Cross section B–B′. See Figure 1.1 for orientation. This section of the Black Warrior Basin is entirely in the subsurface. Datum is the Mississippian-Pennsylvanian contact.

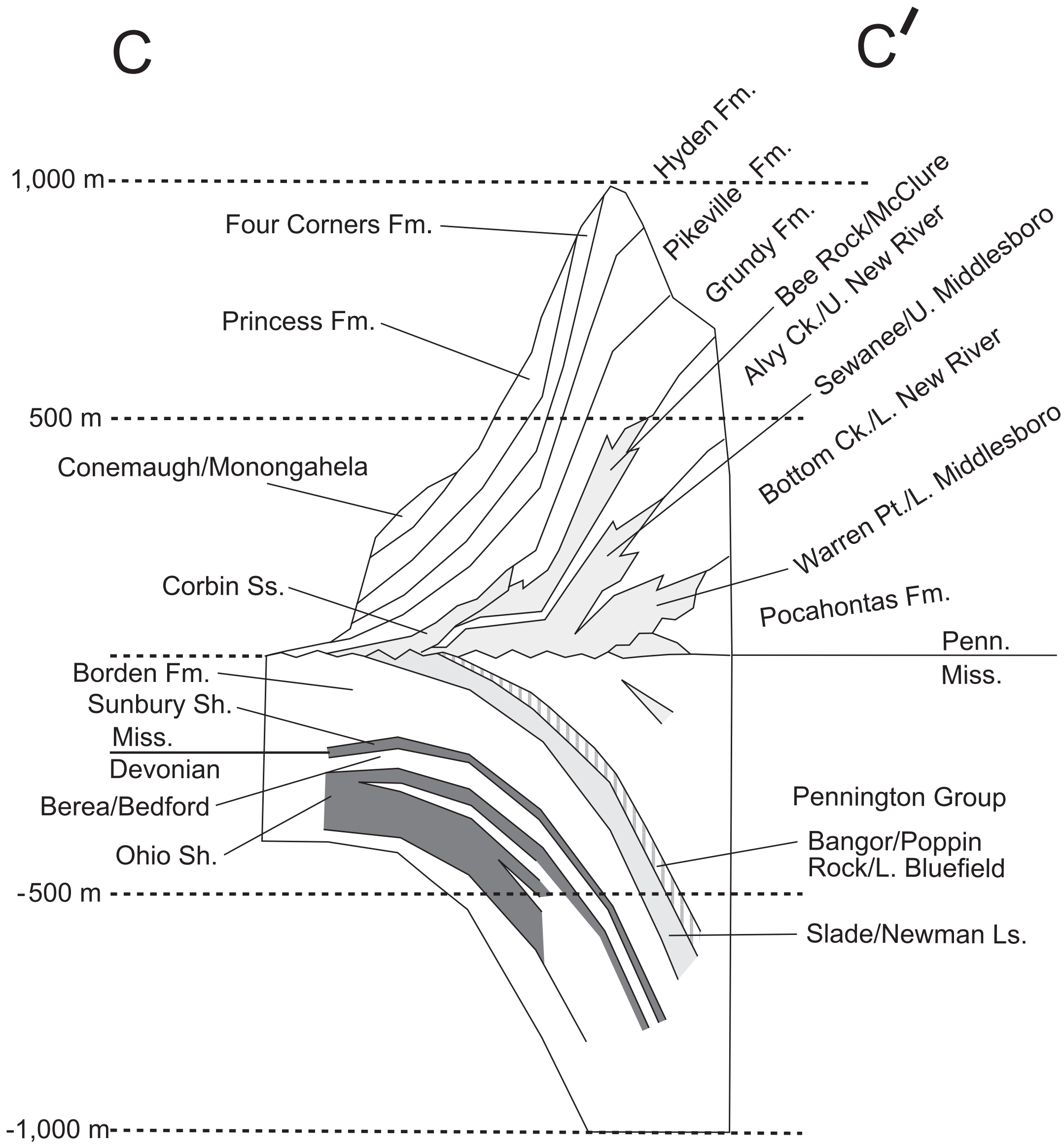

Figure 1.4. Cross section C–C′ of the central part of the Appalachian Basin. See Figure 1.1 for orientation. Datum is the Mississippian-Pennsylvanian contact.

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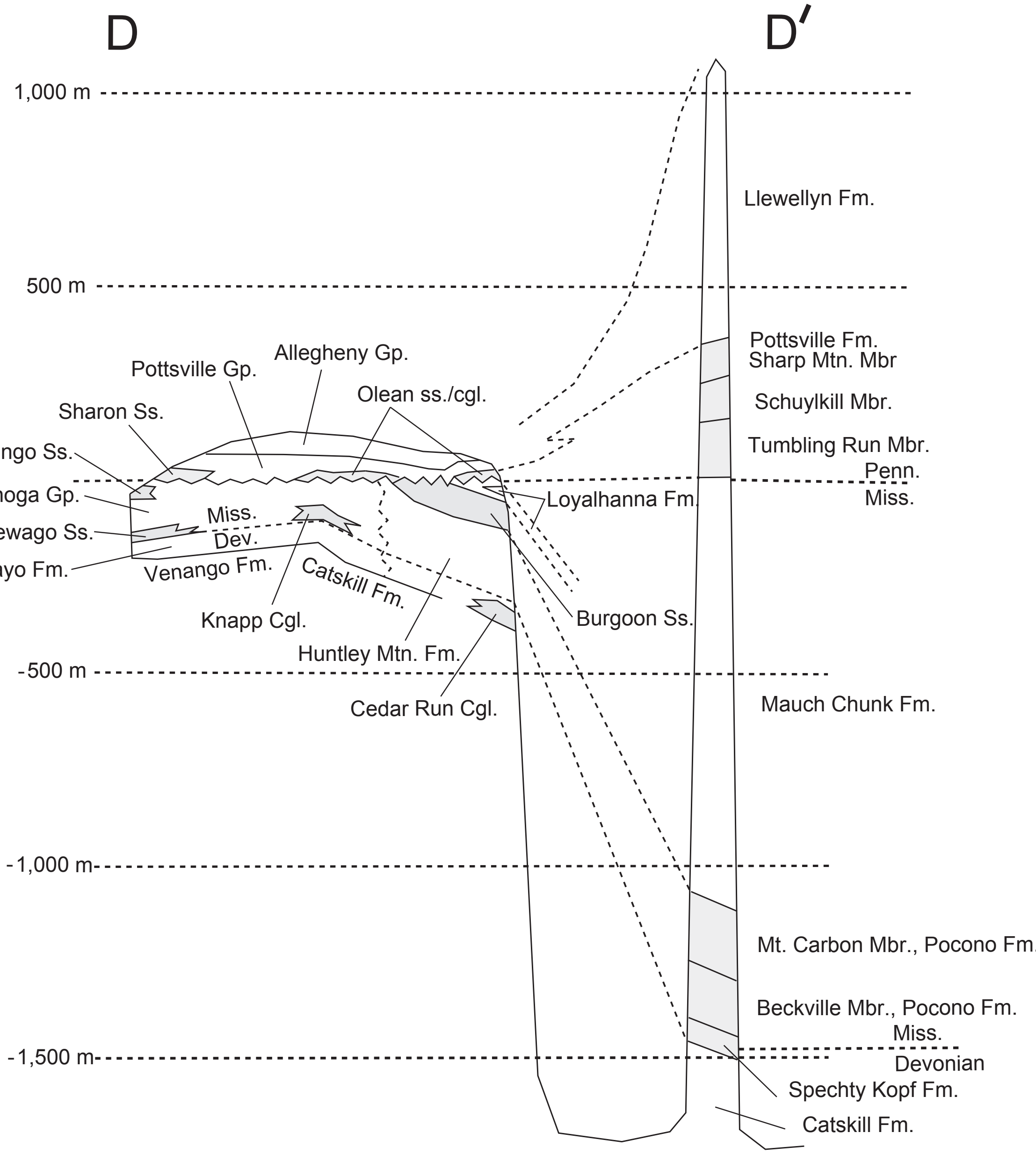

Figure 1.5. Cross section D–D′ of the northern part of the Appalachian Basin. See Figure 1.1 for orientation. Datum is the Mississippian-Pennsylvanian contact.

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2: Carboniferous of the Black Warrior Basin

Jack C. Pashin and Robert A. Gastaldo

Geologic Setting

The Black Warrior Basin is a late Paleozoic foreland basin in Alabama and Mississippi that lies adjacent to the juncture of the Appalachian and Ouachita orogenic belts (Mellen, 1947; Thomas, 1973, 1977) (Fig. 2.1). The basin formed during the early stages of Pangaean supercontinent assembly, and the sedimentary fill reflects the tectonic evolution of the basin, as well as climatic changes related to drift through the southern tradewind belt into the equatorial zone (Thomas, 1988; Pashin, 1993, 1994a). The basin has a triangular plan and is bounded on the southwest by the Ouachita orogen, on the southeast by the Appalachian orogen, and on the north by the Nashville Dome. A southeast-plunging nose of the Nashville Dome separates the Black Warrior Basin from the Appalachian Basin (Thomas, 1988). Carboniferous strata are preserved throughout the Black Warrior Basin and in adjacent parts of the Appalachian thrust belt, and these regions originally constituted a single depositional basin that Thomas (1997) referred to as the greater Black Warrior Basin, which is the subject of this paper. Outcrops of these strata are accessible in the Appalachian thrust belt and the eastern part of the Black Warrior Basin, but the western two-thirds of the basin and adjacent parts of the Ouachita orogen are concealed below the Mesozoic-Cenozoic fill of the Gulf of Mexico Basin.

Intersection of the Appalachian and Ouachita orogens at nearly right angles had a strong effect on evolution of the Black Warrior Basin (Thomas, 1976, 1995) (Fig. 2.1). The basin is developed on the Alabama Promontory, a protuberance of the Laurentian continental margin that formed during Early Cambrian Iapetan rifting (Thomas, 1977, 1991). The southwest margin of the promontory remained passive until Late Mississippian time, when the Black Warrior foreland basin was initiated by obduction of a Ouachita accretionary prism (Thomas, 1976; Viele and Thomas, 1989). Convergence along the southeastern, or Appalachian, margin of the promontory began during the Ordovician Taconic Orogeny. Although rift-related basement faults were reactivated at various times during the Paleozoic (Thomas, 1968, 1986), it was not until the Early Pennsylvanian that an orogenic sediment source and subsidence center developed along the southeastern margin of the basin (Sestak, 1984; Pashin and others, 1991).

Lithostratigraphy

Mississippian System

The Devonian-Mississippian boundary is generally considered to be at the base of the Maury Shale (Fig. 2.2), which contains a late Kinderhookian–early Osagean conodont fauna and overlies the black, fissile Chattanooga Shale (Conant and Swanson, 1961; Drahovzal, 1967). The Maury is generally thinner than 1 m and is a gray shale containing glauconite and phosphate nodules. Conant and Swanson (1961) considered both contacts of the Maury to be disconformable. Above the Maury is the Fort Payne Chert, which is a fossilifer-

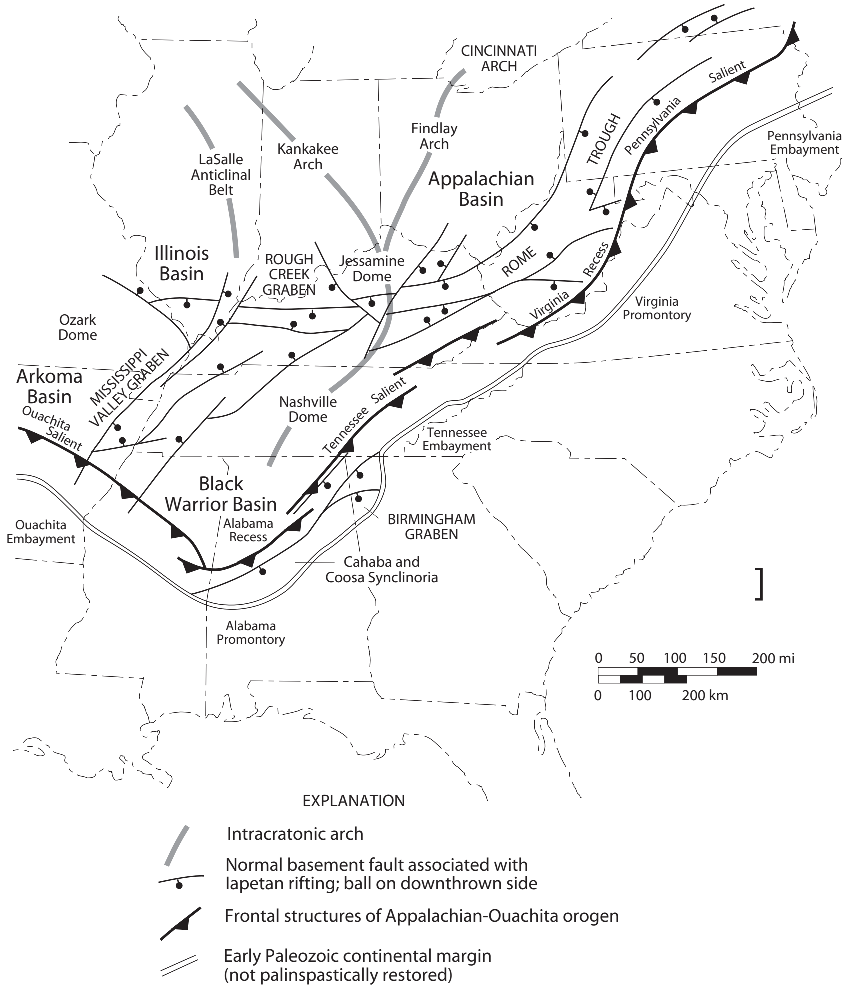

Figure 2.1. Tectonic setting of the Black Warrior foreland basin (after Thomas, 1988). Reprinted with permission of Geological Society of America.

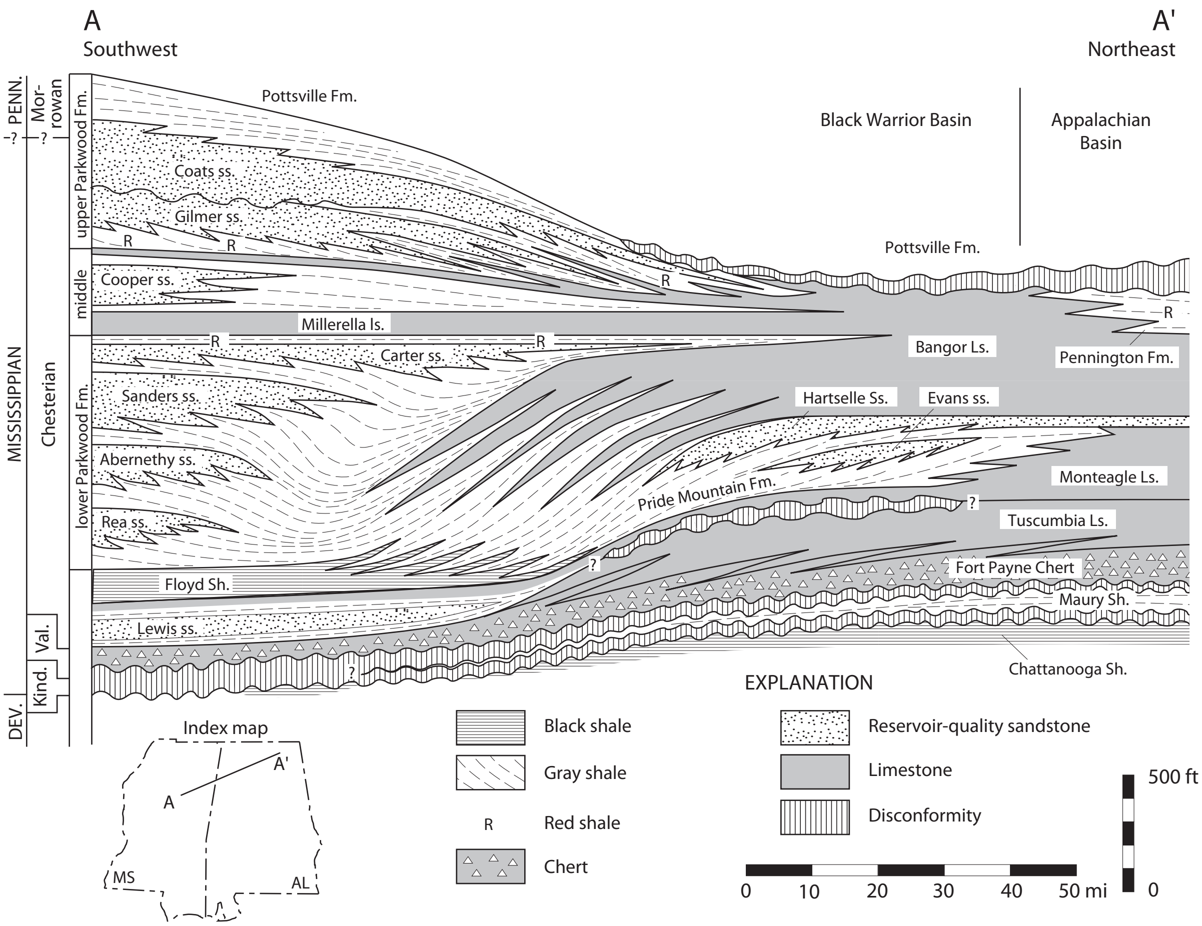

Figure 2.2. Generalized Mississippian stratigraphy of the Black Warrior Basin along a transect from northeastern Alabama to east-central Mississippi (after Pashin, 1994a). Reprinted with permission of Gulf Coast Association of Geological Societies.

ous unit dominated by dark micrite and nodular chert (Butts, 1926). The Fort Payne grades upward into the Tuscumbia Limestone, which is dominated by calcarenite (Thomas, 1972). The Fort Payne generally is considered to be of Osagean age, whereas the Tuscumbia bears Meramecian faunas (Ruppel, 1979). These two units thin southwestward from more than 125 m to less than 25 m, and as they thin, the Tuscumbia passes into a chert-rich facies that is indistinguishable from the Fort Payne (Thomas, 1972, 1988).

The Chesterian Series is cyclic and constitutes the bulk of the Mississippian System in the Black Warrior Basin, reaching a thickness exceeding 1,100 m adjacent to the Ouachita orogen in Mississippi. A subtle disconformity separates Meramecian and Chesterian strata along the northern margin of the basin (Pashin and Rindsberg, 1993) (Figs. 2.2–2.3). Carbonate rocks dominate the Chesterian Series in the northeastern part of the basin, whereas siliciclastic rocks are prevalent in the southwestern part. The Monteagle Limestone is the basal Chesterian unit in the northeastern part of the basin and is dominated by oolitic calcarenite (Handford, 1978). The Monteagle is generally thinner than 50 m and passes southwestward into cyclically interbedded shale, sandstone, and limestone of the Pride Mountain Formation (Welch, 1958, 1959). The Pride Mountain contains two quartzarenite units informally named the Lewis sandstone and the Evans sandstone, which are important hydrocarbon reservoirs in northeastern Mississippi and west-central Alabama (Cleaves, 1983). Above the Pride Mountain Formation is the quartzarenitic Hartselle Sandstone, which is locally thicker than 35 m and contains abundant asphaltic hydrocarbons (Thomas and Mack, 1982; Wilson, 1987). Together, the Pride Mountain Formation and Hartselle Sandstone reach a maximum thickness of 120 m.

The Hartselle Sandstone is overlain by the Bangor Limestone (Figs. 2.2–2.3), which extends to the top of the Chesterian Series in the northeastern part of the basin and is locally thicker than 135 m (Thomas, 1972; Thomas and others, 1979). The Bangor contains a spectrum of carbonate rock types; oolitic and skeletal calcarenite are the most characteristic lithologies. The upper part of the Bangor can be dolomitic and includes intervals of red and greenish-gray mudstone. Although a carbonate facies dominates the northeastern part of the greater Black Warrior Basin, siliciclastic facies of the Floyd Shale and Parkwood Formation dominate the southwestern part and locally are thicker than 950 m. Facies relationships between the carbonate and siliciclastic facies are com-

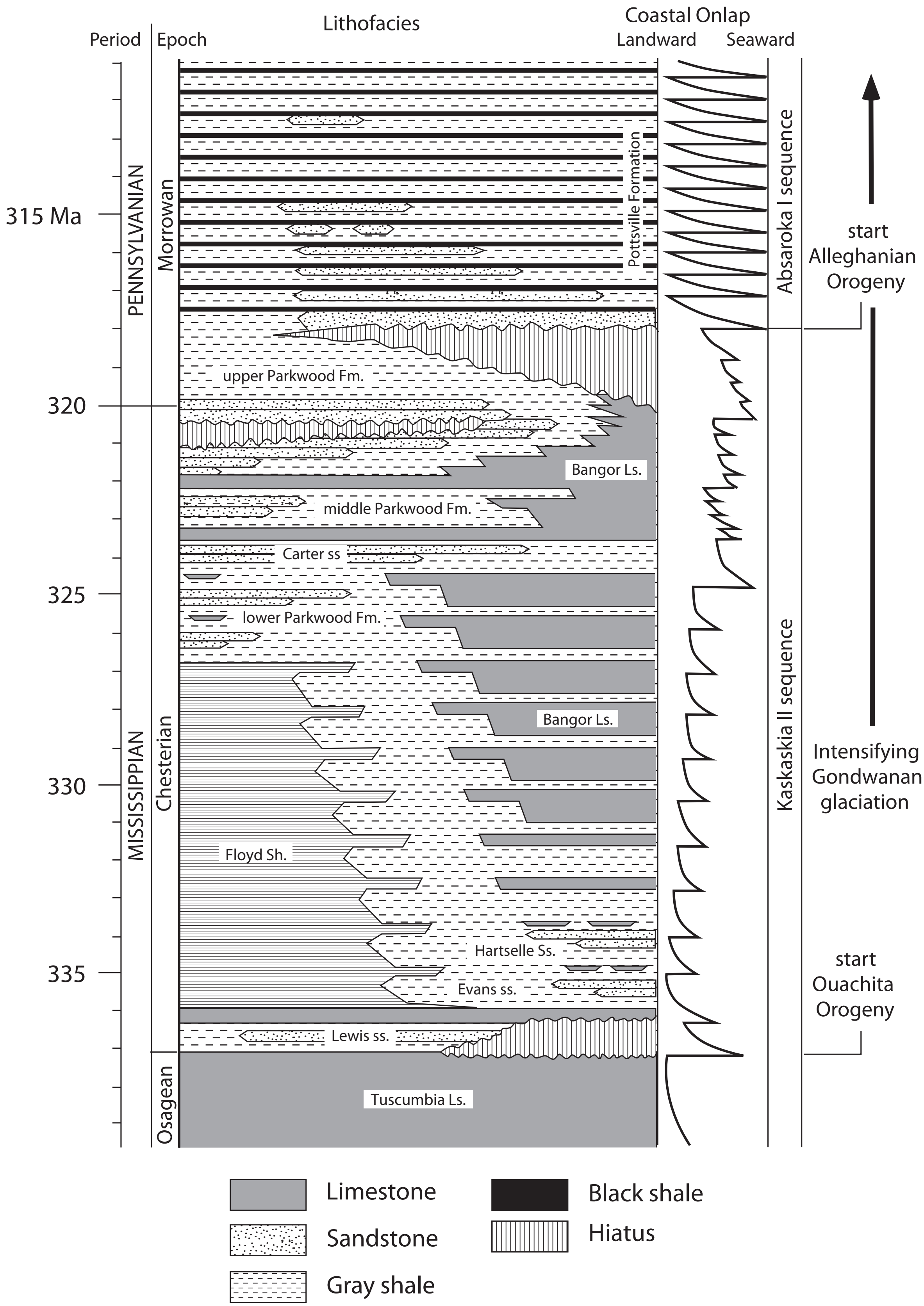

Figure 2.3. Wheeler diagram showing facies, cycles, and coastal onlap curve for Chesterian and Morrowan rocks of the Black Warrior Basin (after Pashin, 1994a). Reprinted with permission of Gulf Coast Association of Geological Societies.

plex. The lower part of the Bangor has clinoform geometry and passes southwestward into dark shale of the Floyd Shale (Pashin, 1993; Mars and Thomas, 1999). The Floyd Shale coarsens upward into the lower part of the Parkwood Formation, which is composed primarily of interbedded sandstone and shale, and contains the Carter sandstone, which is the most prolific conventional hydrocarbon reservoir in the basin. The middle part of the Parkwood is dominated by limestone and shale, and contains a major carbonate tongue that extends basinward above the lower Parkwood from the main body of the Bangor Limestone. Near the base of the Bangor tongue is the Millerella limestone, which contains oobiosparite with the distinctive endothyrid *Eostaffella (Millerella) chesterensis*. The upper Parkwood Formation is composed primarily of siliciclastic rocks and contains some thin, subeconomic coal beds. The upper Parkwood intertongues with the youngest Bangor strata in the northeastern part of the basin, and sandstone within the upper Parkwood ranges in composition from quartzarenite to litharenite (Mack and others, 1981).

Pennsylvanian System

The Mississippian-Pennsylvanian boundary is in the upper Parkwood Formation but has yet to be located precisely in the main part of the Black Warrior Basin. Foraminifera indicate that the upper part of the Bangor Limestone may cross the systemic boundary on the southeast-plunging nose of the Nashville Dome (Rich, 1980) (Figs. 2.2–2.3). In the Appalachian thrust belt, the systemic boundary may be in the upper part of the Parkwood Formation, where a macroflora of mixed affinity has been identified (Butts, 1926; Jennings and Thomas, 1987). The Pennsylvanian part of the Parkwood appears to comprise approximately 10 percent of the formation in the main part of the Black Warrior Basin, whereas approximately 50 percent of the formation is of Pennsylvanian age in parts of the Appalachian thrust belt. Here, the upper Parkwood is lithologically heterogeneous and contains gray shale, sandstone ranging in composition from quartzarenite to litharenite, underclay, and coal.

The Pottsville Formation contains the youngest strata preserved in the greater Black Warrior Basin and forms the majority of the foreland basin fill, with thickness locally exceeding 2,500 m (Fig. 2.4). The Pottsville sharply overlies the Parkwood Formation in the northeastern part of the basin, whereas farther southwest the contact is gradational (Thomas, 1974; Pashin, 1993). The Pottsville Formation is overlain with an angular unconformity by poorly consolidated Cretaceous deposits. The Pottsville is composed principally of shale and sandstone and contains numerous economic coal zones (e.g., Squire, 1890; McCalley, 1900; Rothrock, 1949; Culbertson, 1964) (Fig. 2.4). The coal is used extensively for electric power generation and metallurgy, and forms prolific coalbed methane reservoirs.

Pottsville strata are in three major coal fields (Fig. 2.4). The Warrior coal basin corresponds with the main part of the Black Warrior Basin, and the Cahaba and Coosa Coal Fields are in the Appalachian thrust belt. In the Warrior Coal Field, the Pottsville Formation contains numerous marine-nonmarine depositional cycles, or cyclothems (Fig. 2.5). Each cyclothem begins with a ravinement surface that is overlain by an interval thinner than 1 m containing condensed marine fossil assemblages (Liu and Gastaldo, 1992; Gastaldo and others, 1993; Pashin, 1998). Above this is a thick (10–100 m) gray mudstone unit that coarsens upward into sandstone and conglomerate ranging in composition from quartzarenite to litharenite. The sandstone, in turn, is overlain by a heterogeneous coal zone that forms the top of each cycle and consists of mudstone, sandstone, conglomerate, underclay, and coal.

Pashin and others (1995) subdivided the Pottsville Formation of the Cahaba Coal Field into three magnafacies called the Quartzarenite measures, the Mudstone measures, and the Conglomerate measures (Figs. 2.4, 2.6). The Quartzarenite measures are approximately 300 m thick and contain two regionally extensive sandstone units called the Shades and Pine Members. The Mudstone measures are in places thicker than 1,400 m and contain gray mudstone, sandstone, underclay, and coal. These strata resemble the cyclic, economic coal-bearing strata of the Warrior Coal Field. The frequency of marine deposits decreases markedly upsection, however. The Conglomerate measures form the upper 750 m of the Pottsville, and conglomerate containing extraformational lithoclasts is the signature lithology of the magnafacies. Conglomerate units are commonly thicker than 60 m and are separated by coal zones. Only one marine interval has been identified in the conglomerate measures.

The Pottsville section in the Coosa Coal Field also has been divided into three magnafacies named the Quartzarenite measures, the Redbed measures, and the Mudstone measures (Pashin, 1997) (Fig. 2.4). The Quartzarenite measures are approximately 500 m thick and contain abundant quartz pebbles compared to the Cahaba Coal Field. The Redbed measures, which are approximately 1,200 m thick, are characterized by intervals of brownish-gray (red) mudstone that are up to 15 m thick (Butts, 1927). Between the red intervals, the Redbed measures resemble the Cahaba Mudstone measures. The Mudstone measures form the upper 1,000 m of the Coosa section and resemble the lower part of this magnafacies in the Cahaba Coal Field.

The Pottsville Formation of Alabama has long been thought to be of Early Pennsylvanian age (Butts, 1926), but biostratigraphic subdivision has been elusive (Cropp, 1960; Upshaw, 1967; Eble and Gillespie, 1989) (Figs. 2.2, 2.4). The base of the Pottsville is not dated, but palynomorphs from near the top of the Parkwood Formation indicate a Namurian C or younger age (Eble

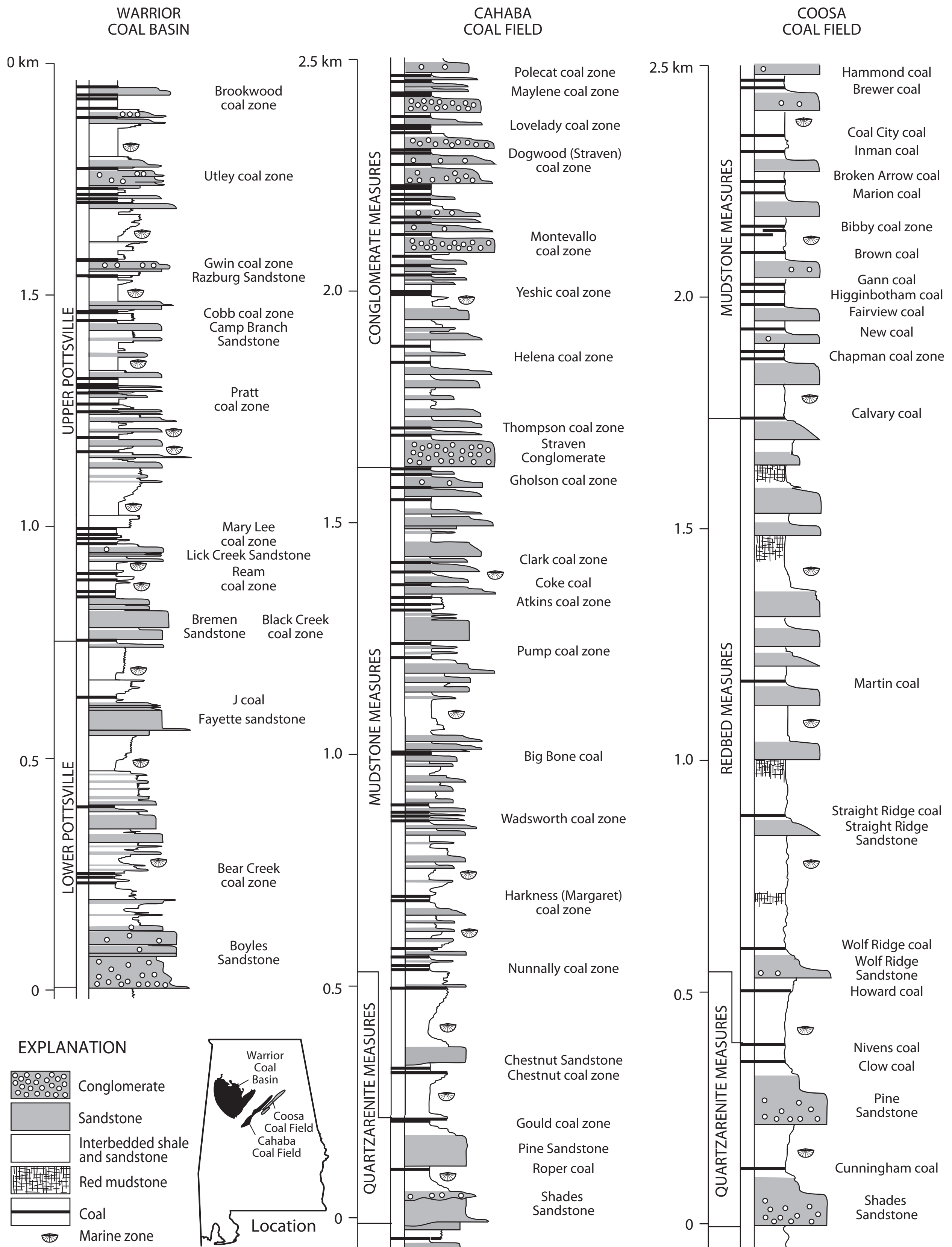

Figure 2.4. Generalized stratigraphic sections of the Pottsville Formation in the three major coal fields of the greater Black Warrior Basin in Alabama.

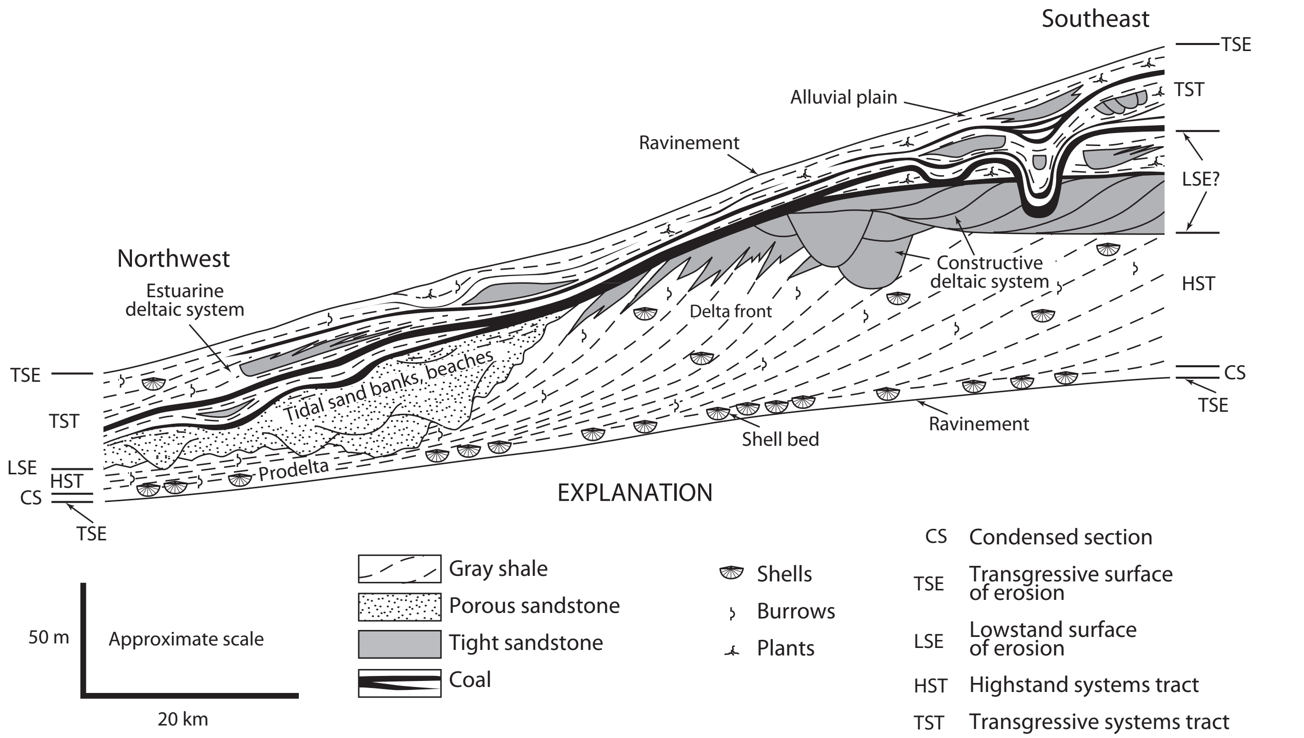

Figure 2.5. Idealized cyclothem in the Pottsville Formation of the Warrior coal basin (after Pashin, 1998). Reprinted from *International Journal of Coal Geology*, v. 35, with permission of Elsevier.

and others, 1991). Palynomorph and marine invertebrates suggest that strata from the Black Creek through Brookwood coal zones are of Langsettian age (Eble and Gillespie, 1989), although macroflora may suggest that some strata are of Duckmantian age (Lyons and others, 1985). Several depositional cycles younger than the Brookwood coal zone are preserved in the structurally deepest parts of the Warrior Coal Field (Henderson and Gazzier, 1989), but the age of these strata is unknown. Eble and others (1991) suggested on the basis of palynomorphs that the youngest strata in the Cahaba Coal Field are approximately equivalent to the Brookwood coal zone in the Warrior field. Presence of marine strata throughout the Mudstone measures of the Coosa field led Pashin (1997) to suggest that these strata are no younger than the Mudstone measures in the Cahaba field.

Depositional History

Mississippian System

The Devonian-Mississippian transition was marked by cessation of Chattanooga black-shale deposition and accumulation of the thin, phosphatic, and glauconitic Maury Shale (Fig. 2.2), thus signaling regional oxygenation, extreme condensation, and perhaps upwelling during Kinderhookian time (Pashin, 1993). Carbonate ramp deposition dominated Osagean and Meramecian time, as exemplified by the Fort Payne Chert and Tuscumbia Limestone. The Fort Payne is considered a lower ramp deposit. Abundant chert, sponge spicules, and a crinoid-bryozoan fauna indicate cool water, and upwelling along the Ouachita margin is thought to have been a source of silica and nutrients (Gutschick and Sandberg, 1983). The Tuscumbia Limestone contains mid- and upper-ramp deposits and includes a skeletal-shoaled bank rim (Fisher, 1987).

The mixed carbonate-siliciclastic deposits of the Chesterian Series reflect major changes of the tectonic and paleoceanographic setting of the Black Warrior Basin (Figs. 2.2–2.3). The disconformity at the base of the Pride Mountain Formation marks inception of major Ouachita orogenesis on the Alabama Promontory (Pashin and Rindsberg, 1993), and part of the Pride Mountain Formation, which includes the Lewis sandstone, was deposited as part of a lowstand wedge (Stapor and Cleaves, 1992). At this time, carbonate ramp deposits, as embodied by the oolitic Monteagle Limestone, retreated to the extreme northeastern part of the basin. The Pride Mountain Formation and Hartselle Sandstone contain mainly beach and tidal facies. The source of the siliciclastics is controversial; some workers favor cratonic sources (e.g., Cleaves and Broussard, 1980; Driese and others, 1994) and others favor sources in the Ouachita orogen (e.g., Thomas, 1974; Thomas and Mack, 1982).

The Bangor Limestone indicates renewed progradation of a shoal-rimmed carbonate ramp into the basin (Thomas and others, 1979), although the dark, organic-rich Floyd Shale suggests that circulation in lower ramp environments became restricted by tectonic closure (Pashin, 1993) (Figs. 2.2–2.3). The lower Parkwood Formation is of deltaic origin and includes delta-de-

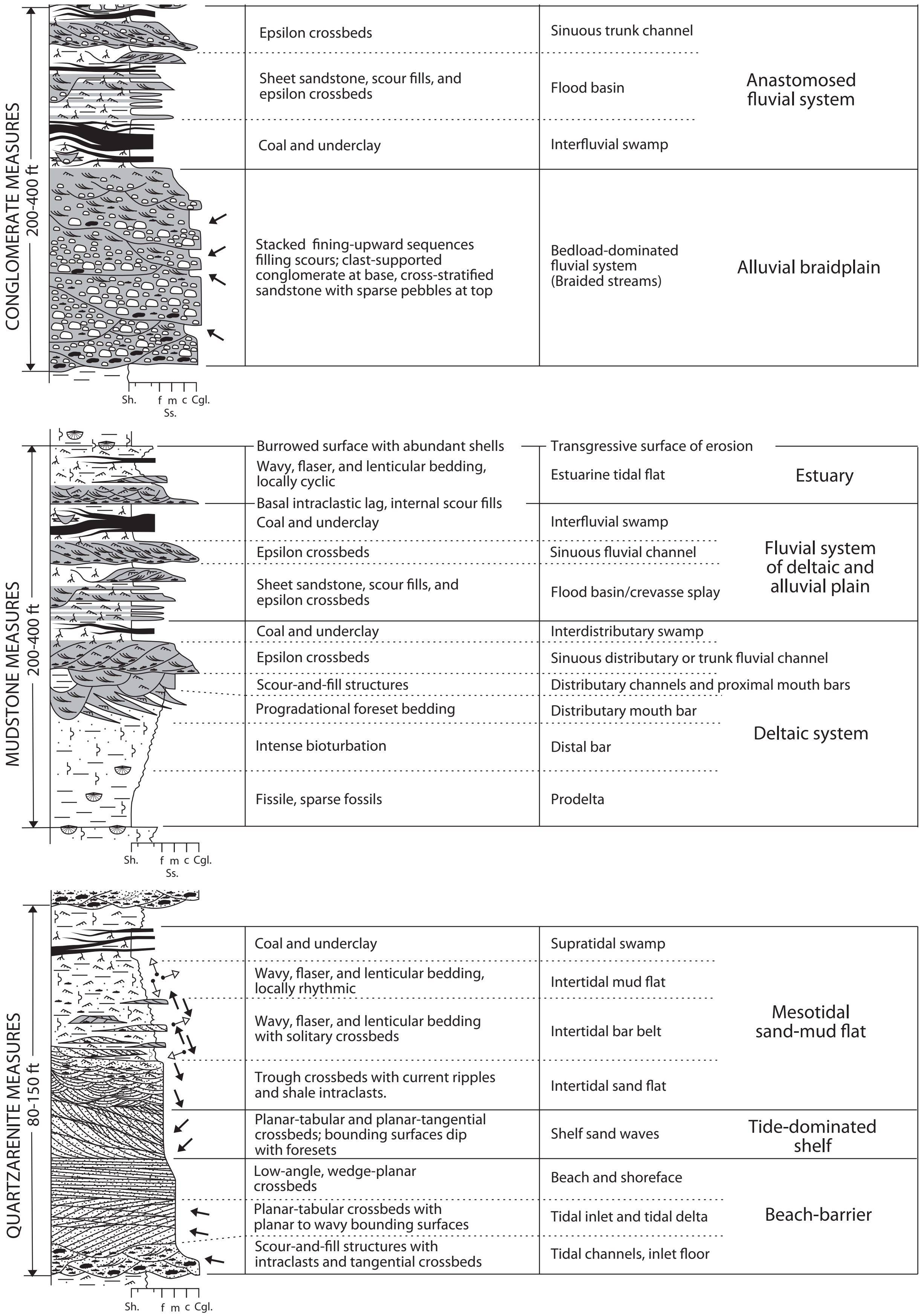

Figure 2.6. Paleonvironmental interpretation of Pottsville magnafacies in the Cahaba Coal Field (after Pashin and others, 1995). See explanation on next page. Reprinted with permission of the Geological Survey of Alabama.

structive beach facies (Pashin and Kugler, 1992). Again, some workers postulate cratonic sediment sources (e.g., Welch, 1978; Cleaves, 1983), and others postulate orogenic sources (e.g., Thomas, 1988; Mars and Thomas, 1999). The middle Parkwood heralds marine transgression and a brief return to regionally extensive carbonate sedimentation. The upper Parkwood represents a renewed progradation of deltaic sediment that spans the Mississippian-Pennsylvanian boundary (Thomas, 1972; Thomas and others, 1991).

Pennsylvanian System

Paleogeographic reconstructions indicate that the Black Warrior Basin migrated through the southern tradewind belt into the equatorial rainy belt during the Carboniferous (Scotese and Golonka, 1992). This migration is reflected in the transition from a thick carbonate succession containing red, vertic paleosols to a siliciclastic-dominated succession containing coal and underclay (Pashin, 1994a). This transition indicates a change from a semi-humid or semi-arid climate to the everwet equatorial climate that prevailed in eastern North America during the Early Pennsylvanian (Cecil, 1990). In concert with this climatic change was development of the sub-Absaroka cratonic sequence boundary, which corresponds with the base of the Pottsville Formation in the greater Black Warrior Basin (Thomas, 1988). Pottsville strata are locally in contact with Mississippian strata (Henry and others, 1985), but the sub-Absaroka boundary is developed within the Pennsylvanian System across most of the greater basin, having minimal time value and minimal paleotopographic relief (Thomas, 1988). The sub-Absaroka sequence boundary marks a significant tectonic reorganization of the main Black Warrior Basin in which an Appalachian subsidence center was superimposed on the older Ouachita foreland basin. It was not until deposition of the Mary Lee coal zone (Fig. 2.4) that the Appalachian orogen began supplying a significant quantity of coarse-grained sediment to the main part of the Black Warrior Basin (Pashin, 1999).

McCalley (1900) recognized the clustering of coal beds into discrete zones, and Butts (1926) recognized evidence for repeated marine transgressions and regressions during Pottsville deposition. The Warrior coal basin played a central role in the development of fluvial-deltaic and barrier-shoreline facies models for Pennsylvanian coal-bearing strata (e.g., Ferm and others, 1967; Hobday, 1974; Ferm and Weisenfluh, 1989). It was not until recently, however, that investigators acknowledged the importance of allogenic depositional cyclicity in these strata (e.g., Gastaldo and others, 1993; Pashin, 1994a; Demko and Gastaldo, 1996). Following the lead of Liu and Gastaldo (1992), Pashin (1994a, b, 1998) defined 13 regionally extensive, flooding-surface-bounded depositional cycles between the base of the Pottsville and the top of the Brookwood coal zone (Figs. 2.4–2.5). Although there is considerable geochronologic uncertainty, these cycles appear to be the products of glacial-eustatic forcing associated with Milankovitch orbital eccentricity (Fig. 2.2).

Similar forcing mechanisms were probably active in the Quartzarenite and Mudstone measures of the Cahaba Coal Field (Fig. 2.6), but evidence for progressive terrestrialization stands in stark contrast to the persistent cyclicity in the Warrior coal basin. Indeed, extraformational conglomerate in the Conglomerate measures has been interpreted as bedload-dominated fluvial deposits (Osborne, 1991), and the intervening coal zones are thought to contain anastomosed fluvial deposits (Pashin and others, 1995). There is evidence for limited tectonic translation of the Cahaba thrust sheet and direct evidence for growth strata in the Sequatchie Anticline of the Warrior coal field (Pashin, 1994c, 1998). Consequently, Pashin and others (1995) suggested that accumulation of sediment behind an uplifting blind thrust ridge facilitated terrestrialization of the Cahaba field while permitting free oscillation of the shoreline in the Warrior field.

The Cahaba and Coosa Coal Fields contain the thickest successions of Lower Pennsylvanian strata in the United States. Considering that the youngest strata in the Coosa field may be no younger than the Mudstone measures in the Warrior field (Fig. 2.4), the tectonic subsidence rate must have been remarkable in

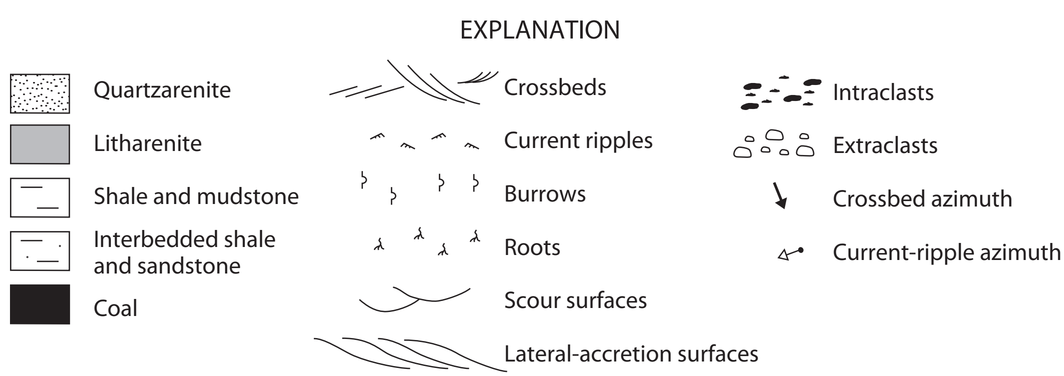

Figure 2.6. Paleonvironmental interpretation of Pottsville magnafacies in the Cahaba Coal Field (after Pashin and others, 1995). Explanation—Continued from previous page. Reprinted with permission of the Geological Survey of Alabama.

the Coosa Synclinorium, perhaps exceeding 400 m/my. Depositional history in the Coosa Coal Field roughly paralleled that in the quartzarenite measures and mudstone measures of the Cahaba Coal Field, but the Coosa redbeds represent a unique facies in the Pennsylvanian strata of North America. On the basis of extreme oxidation and possible occurrences of plinthite, Pashin (1997) and Bearce and Kassaw (1999) interpreted the redbeds as lateritic paleosols that formed upland of the major peat swamps that flourished in the Warrior and Cahaba Coal Fields.

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3: The Mississippian of the Appalachian Basin

Frank R. Ettensohn

Geologic Setting

The Mississippian rocks of the Appalachian Basin are among the most prominent in the basin because of the thick section of relatively pure carbonates that characterizes middle parts of the system in most areas. Although present throughout the basin from extreme southwestern New York to northeastern Alabama and northwestern Georgia, exposures are confined to a wide band around the present margin of the basin. The system attains its maximum basinal thickness of nearly 1,500 m in east-central Pennsylvania and has a minimal thickness of 9 m in southwestern New York. Throughout the basin, it is commonly bounded by unconformities at its base and top (Fig. 3.1). In small areas in east-central Pennsylvania, southern West Virginia, southwestern Virginia, and northeastern Alabama, however, the Mississippian-Pennsylvanian systemic boundary may be conformable (Fig. 3.2). The unconformity with the Devonian System is more subtle and difficult to recognize, and in parts of Pennsylvania, West Virginia, and West Virginia may also be gradational. The presence of bounding unconformities in effect makes the Mississippian System of the Appalachian Basin a typical third-order stratigraphic sequence in the sense of Vail and others (1977).

Tectonic Framework

The Mississippian section in the Appalachian Basin occupies a flexural foreland basin that reflects influence by three orogenies: the Acadian, Alleghanian, and Ouachita. Moreover, in response to these orogenies, basement structures were periodically reactivated and had substantial influence on the nature of the Mississippian section (e.g., Dever, 1980; Ettensohn, 1980, 1981).

The Acadian Orogeny represents a north-to-south, transpressive collision between the southeastern margin of Laurussia and various Avalonian terranes. Although the orogeny was largely a Middle and Late Devonian event, structural and stratigraphic evidence indicates that the orogeny continued into Mississippian time (Ettensohn, 1985, 1998a). In fact, the last Acadian tectophase probably represents latest Devonian–Early Mississippian convergence at the southeastern margin of Laurussia (McClellan and others, 2005a, b; Hatcher and others, 2003, 2005), and most of the Mississippian section may reflect a subsequent relaxational response (e.g., Ettensohn and Pashin, 1993; Ettensohn and others, 2002; Ettensohn, 2004, 2005, 2008). This interpretation is in marked contrast to the more commonly accepted idea that the Upper Mississippian clastic sequence reflects the inception of the Alleghanian Orogeny (e.g., Davis and Ehrlich, 1974; Perry, 1978; Milici and deWitt, 1988; Chesnut, 1991).

The Alleghanian Orogeny reflects the clockwise convergence of African parts of Gondwana with Laurussia. The clockwise convergence of Gondwana toward Laurussia (e.g., Ziegler, 1989), the age and distribution of clastic wedges in the foreland basin (Chesnut, 1989; Patchen and others, 1985a, b), and flexural modeling (Beaumont and others, 1987, 1988) suggest that the orogeny progressed from south to north. Consequently, in south and central parts of the orogen, the inception of subsurface Alleghanian thrusting and related uplift may also have begun as early as Late Mississippian time (Goldberg and Dallmeyer, 1997). Moreover, if the widespread uplift and erosion on the Mississippian-Pennsylvanian (or sub-Absaroka) unconformity is interpreted to represent bulge moveout and uplift at the inception of orogeny (Quinlan and Beaumont, 1984), then the Early Pennsylvanian age of that unconformi-

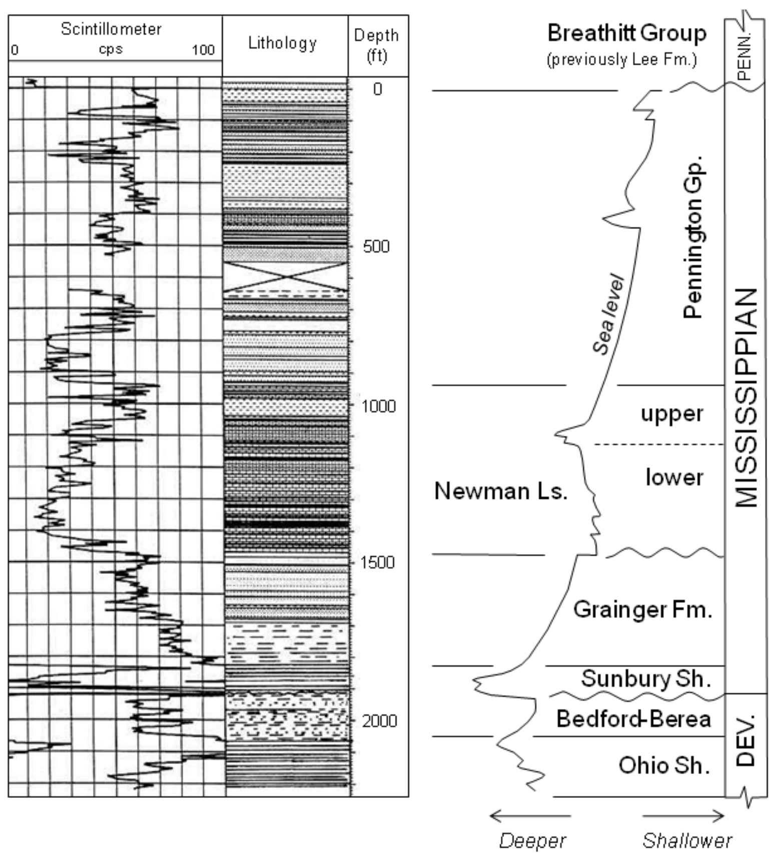

Figure 3.1. A typical lithologic column and scintillometer (gamma ray) profile for Mississippian rocks in the Appalachian Basin based on a section at Pound Gap, Ky., with a corresponding, inferred sea-level curve on the right.

ty (Englund and others, 1979) must indicate an Early Pennsylvanian age for the inception of orogeny along more southern parts of the colliding continental margin.

The Ouachita Orogeny on the southern or Ouachita margin of Laurussia records the final phase of collision between Laurussia and Gondwana, and stratigraphic evidence does suggest that the orogeny influenced patterns of sedimentation and the distribution of unconformities throughout Mississippian time in southern parts of the Appalachian Basin (Ettensohn and Pashin, 1993, 1997; Ettensohn, 1994; Ettensohn and others, 2002).

Eustatic Framework

The Mississippian Period also saw the onset of Gondwana glaciation (Frakes and others, 1992; Cecil and others, 2004) and with it important glacial-eustatic sea-level changes. Despite active tectonism in various parts of the Appalachian Basin, fourth- and fifth-order eustasy generated regionally correlative sequences in the Mississippian record across the basin. The most important effects of Mississippian eustasy have been discussed by Ettensohn (1998b), Miller and Eriksson (1999), Ettensohn and others (2003, 2004), Al-Tawil and Read (2003), and Al-Tawil and others (2003).

Lithostratigraphy

The Mississippian System of the Appalachian Basin is part of a foreland-basin succession. Although the system is locally absent in parts of the Appalachian Basin because of post-depositional erosion, its thickness ranges from as little as 32 m in southwestern New York to as much as 1,900 m in southeastern Pennsylvania (Edmunds and others, 1979; Patchen and others, 1985a, b). The system generally exhibits a three-part stratigraphic sequence composed of Lower and mid-Mississippian (Tournaisian–early Viséan; Kinderhookian–Osagean) clastic sediments, Middle and Upper Mississippian (middle–late Viséan; Meramecian–early Chesterian) carbonates, and uppermost Mississippian (latest Viséan–Serpukhovian; late Chesterian) clastic sediments (Figs. 3.1–3.2). These sequences are traditionally interpreted to represent post-Acadian clastic influx, widespread carbonate deposition accompanying tectonic quiescence, and renewed clastic influx marking inception of the Alleghanian Orogeny, respectively (Rice and others, 1979; Ettensohn and others, 2002; Ettensohn, 2004). In western parts of the basin, the base of the lower clastic sequence is a subtle unconformity beneath the Maury, Fort Payne, or Sunbury formations (Milici and others, 1979; Patchen and others, 1985a; Ettensohn and others, 1988a; Woodrow and others, 1988; Ettensohn and Pashin, 1997), whereas in central, eastern, and northern parts of the basin, the Devonian-Mississippian transition is gradational (Edmunds and others, 1979; Englund, 1979; Arkle and others, 1979; Edmunds, 1996).

Overlying the unconformity in western parts of the basin, and beginning the Mississippian System in most parts of the basin, is the widespread, fissile, black Sunbury Shale and its equivalents, which are typically 4 to 15 m thick (Figs. 3.1–3.2). Earlier interpretations had suggested that the Devonian-Mississippian boundary occurred below or within the underlying Bedford-Berea sequence (e.g., Pepper and others, 1954), but more recent palynological data from Ohio and Kentucky indicate that the Bedford-Berea is entirely Late Devonian in age (Molyneaux and others, 1984; Coleman and Clayton, 1987), meaning that the unconformity below the Sunbury marks the systemic boundary. In central and eastern parts of the basin, where the underlying unconformity is absent, brown to black marine shales equivalent to the Sunbury are included in the Big Stone Gap Member of the Chattanooga Shale (Stose, 1923; Roen and others, 1964), as well as in the Price, Rockwell, or Pocono formations (Arkle and others, 1979; Edmunds and others, 1979; Englund, 1979; Patchen and others, 1985a,b; Edmunds, 1996) (Fig. 3.2).

Overlying the Sunbury are the deltaic clastics of the Borden, Grainger, Price, and Pocono Formations, as well as the Waverly Group (Figs. 3.1–3.2). The Borden, Grainger, and Waverly, 60 to 200 m thick, contain exclusively marine, prodelta, and delta-front deposits (Hasson, 1972; Edmunds and others, 1979; Chaplin, 1980), whereas the Price and Pocono Formations, 60 to 400 m thick, include progressively more nonmarine, delta-plain sediments upward in the section and toward the eastern source areas (Bartlett, 1972; Arkle and others, 1979; Ettensohn, 2004). Equivalent clastic units in extreme southern parts of the Appalachian Basin are generally absent at an unconformity near the Kinderhook-Osage boundary (mid-Tournaisian) or replaced by 5 to 90 m of cherty, deep-water carbonates of the Fort Payne Formation (Gutschick and Sandberg, 1983) (Fig. 3.2). Although this Kinderhook-Osage unconformity is not present in north and central parts of the Appalachian Basin, it is very prominent throughout the south-central and central United States and probably reflects uplift associated with Ouachita convergence at the southern margin of Laurussia, which appears to have begun by late Kinderhookian time (Ham and Wilson, 1967; Ettensohn, 1993; Ettensohn and Pashin, 1993, 1997).

Late Osagean time saw the end of deltaic sedimentation throughout most of the basin. In eastern parts of the basin, the red sands and shales and associated evaporites of the Maccrady Formation, 10 to 300 m thick, replace the deltaic Price, Pocono, and Grainger Formations, and have been interpreted to represent a period of structural uplift or sea-level lowstand (Warne, 1990; Ettensohn, 1993; Ettensohn and others, 2002). In western and southwestern parts of the basin, however, a thin but widespread unit of glauconite and phosphorite deposition, a few centimeters to 3 m thick, represented

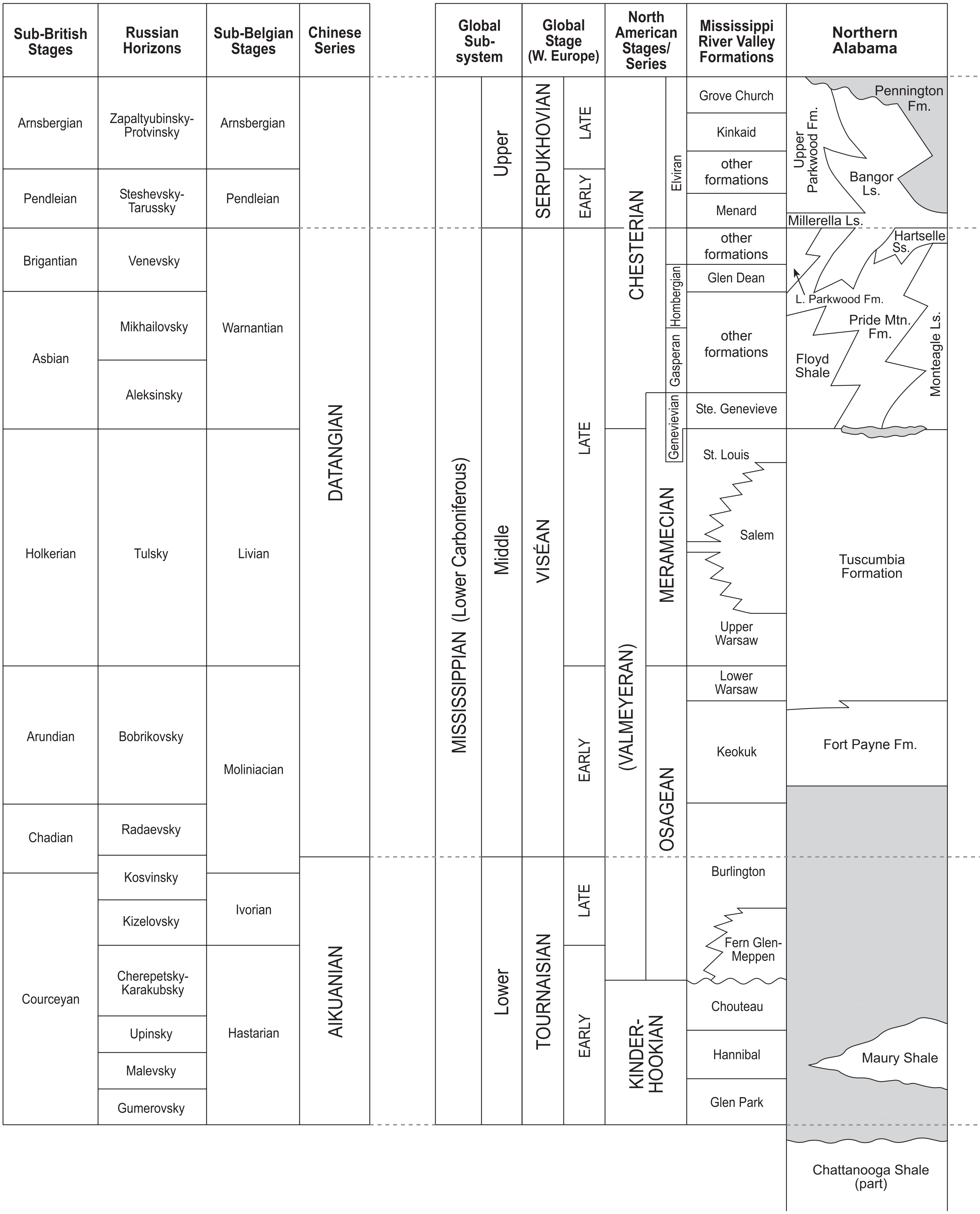

Figure 3.2. Approximate correlation of Mississippian units in parts of the Appalachian Basin. Shaded parts of the section represent missing section or unconformities. Continued on next page.

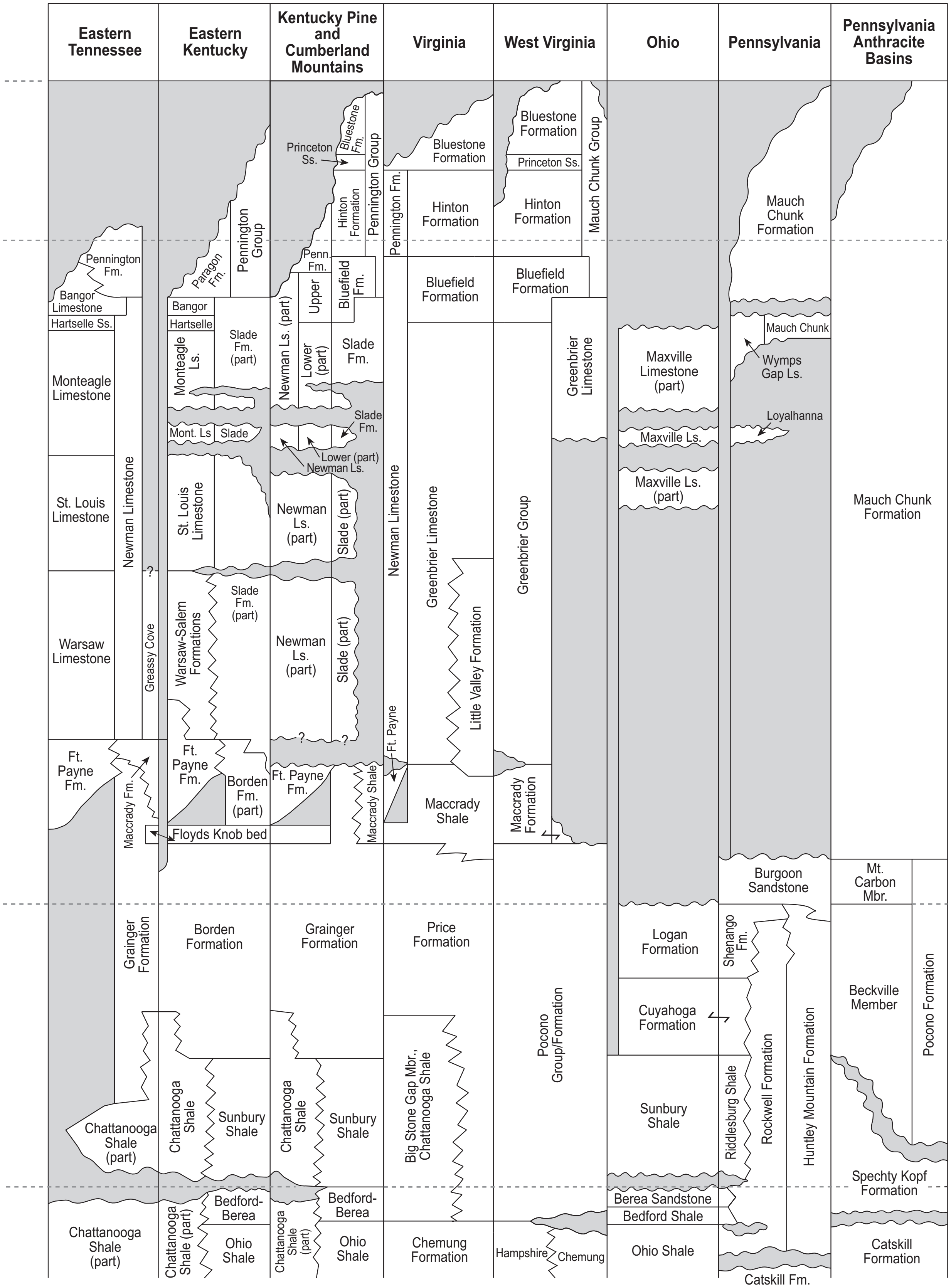

Figure 3.2. Approximate correlation of Mississippian units in parts of the Appalachian Basin. Shaded parts of the section are missing sections. Continued from previous page.

by the Floyds Knob Bed of the Borden and Grainger Formations, forms a prominent marker horizon and has been interpreted to represent a brief interval of clastic starvation accompanying abrupt sea-level rise (Whitehead, 1984). In southern parts of the Appalachian Basin, the Floyds Knob is succeeded by the cherty carbonates of the Fort Payne Formation deposited in deeper waters beyond the shelfbreak (Gutschick and Sandberg, 1983; Whitehead, 1984), whereas in west-central parts of the basin, it is succeeded by regressive, delta-destruction facies in the upper Borden and shallow open-marine to peritidal facies in the Warsaw-Salem Formations and the Renfro Member of the Slade Formation (Ettensohn and others, 2004). In the intervening central parts of the basin, the Grainger Formation persists, but the upper parts of the unit typically contain marine, red sandstones and shales that have been equated to the Maccrady Formation (Wilpolt and Marden, 1959; Ettensohn and others, 2002). Across most of the basin, the Maccrady, upper Grainger, and Fort Payne were truncated during the Osage-Meramec (early Viséan) transition, so that the contact with the overlying Greenbrier or Newman Limestones is generally unconformable. In the eastern United States, this unconformity marks the end of the lower clastic succession. In west- and east-central parts of the basin, however, units such as the Warsaw-Salem, lower Slade (Renfro Member), Greasy Cove, and Little Valley Formations (2–120 m thick) are argillaceous carbonates with major clastic subunits that transition gradationally into the purer carbonates of the middle and upper Slade, Newman, and Greenbrier Limestones.

The middle third of the Mississippian section in the Appalachian Basin is characterized by late Middle to early Late Mississippian (Meramecian–early Chesterian; middle–late Viséan) carbonates of the Newman, Slade, and Greenbrier Limestones (Figs. 3.1–3.2). These attain thicknesses of as much as 350 m. These carbonates represent deposition in widespread, shallow, open-marine environments (e.g., Craig and Connor, 1979; Ettensohn and others, 2002, 2004). An early Chesterian unconformity in basal parts of the carbonate section may reflect a second phase of Ouachita convergence (Ettensohn 1994; Ettensohn and Pashin, 1997). These carbonates grade upward into shales and mixed clastic-carbonate sequences in their upper parts, marking the transition into the clastic-rich upper third of the Mississippian section (Figs. 3.1–3.2).

In western parts of the basin, this transitional, mixed clastic-carbonate sequence is included as the upper part of the Newman Limestone, but in other parts of the basin it is included in the Bluefield Formation or as parts of the Pennington and Mauch Chunk Formations or Groups (Fig. 3.2). These clastic-rich units attain a maximum thickness of more than 1,800 m in eastern Pennsylvania, but more typical thicknesses in other parts of the basin vary from 50 to 450 m (Patchen and others, 1985a, b; Ettensohn, 2004). Although the upper part of the Newman Limestone or Bluefield Formation represents the beginning of major Late Mississippian (late Chesterian; latest Viséan-Serpukhovian) clastic deposition, most Upper Mississippian clastics are included in the Pennington Formation/Group. Various shallow-marine, marginal-marine, and terrestrial environments are commonly represented (e.g., Chesnut and others, 1998; Ettensohn and others, 2002; Greb and others, 2002). Many workers believe that the contact between the Pennington Formation and overlying Pennsylvanian units is nearly everywhere unconformable (e.g., Rice and others, 1979; Chesnut, 1992); however, other interpretations suggest that there may be an intertonguing of "Mississippian-type" and "Pennsylvanian-type" lithologies in the area of the systemic boundary (Edmunds and others, 1979; Englund and others, 1979). In western Virginia and southern West Virginia, however, it has been more convincingly demonstrated that the systemic boundary is probably gradational, and that the largely Mississippian Bluestone Formation of the Pennington Group is laterally and vertically gradational into the largely Pennsylvanian Pocahontas Formation, and that the unconformity, which does progressively truncate earlier Pennsylvanian and Mississippian rocks to the west, is Early Pennsylvanian in age (Englund, 1979). The Mississippian-Pennsylvanian contact is discussed further in the section on the Pennsylvanian of the Appalachian Basin (see Greb and others, *this volume*).

Typical, nearly complete Mississippian sections from the central part of the Appalachian Basin are present at Jellico Mountain, Tenn. (Sedimentation Seminar, 1981; Ettensohn and others, 2002), and at Pound Gap, Ky. (Chesnut and others, 1998; Greb and others, 2002). A similar, exemplary Mississippian section from the western margin of the basin is present at Big Hill, Ky. (Ettensohn and others, 2003; Smath, 2004). Other sections clearly showing the influence of synsedimentary tectonism on the Mississippian sequence have been described in detail from the western margin of the basin along Interstate 64 in northeastern Kentucky (Dever and others, 1977; Ettensohn, 1981, 1986, 1992).

Depositional History

At the end of the Devonian Period, the Appalachian Basin area was located near the southeastern margin of Laurussia. Laurussia was a mid-Paleozoic landmass formed through the convergence of a Laurentian core continent with Baltica in Silurian time (Caledonian Orogeny), with Artica or Chukotka during Silurian-Devonian time (Ellesmerian Orogeny), and with various Avalonian microcontinents during Devonian-Mississippian time (Acadian Orogeny) (e.g., Ettensohn, 1998a). The basin area at this time was largely part of the Acadian foreland basin and was covered by a deep inland sea. A belt of Acadian highlands bordered the continent on the southeast and separated the inland sea from waters of the Rheic Ocean (Ettensohn and others, 1988b). At this time the basin area was located about 20 to 25° south latitude in the subtropical tradewind belt. Because of the continuing clockwise rotation of Gondwana as it closed the Rheic Ocean and converged on Laurussia, however, the Laurussian continent moved progressively more northward during Mississippian time. Hence, by mid-Mississippian time, the basin area had moved within 15 to 20° of the equator, and by latest Mississippian time, the basin area was within 5 to 10° of the equator in the tropical equatorial belt (Scotese, 2003). The presence of thick carbonates and caliche paleosols in middle parts of the Mississippian section of the basin is in part a reflection of the basin's presence in the semiarid tradewind belt at a critical point in time (Ettensohn and others, 1988a). In upper parts of the carbonate section, however, paleosols begin to reflect more humid conditions, and fine-grained clastic sediments become more prevalent (Ettensohn and others, 1988a; Greb and Caudill, 1998). By Late Mississippian time, the carbonate platform was inundated by marginal-marine and terrestrial clastic sediments, which contain a few thin coals. This influx of clastics reflects a major change in sedimentation that was at least partly conditioned by movement of the basin northward into a more humid, tropical climatic belt (Scotese, 2003; Cecil and others, 2004).

The Mississippian System of the Appalachian Basin comprises a third-order sequence defined by an unconformity or abrupt transition at the base of the Sunbury Shale and by an Early Pennsylvanian unconformity at the top (Figs. 3.1–3.2). The Sunbury represents the transgressive systems tract at the base, whereas overlying parts of the clastic-carbonate-clastic sequence represent the succeeding highstand systems tract. In another sense, however, flexural modeling suggests that the typical three-part, clastic-carbonate-clastic Mississippian succession is mostly of tectonic origin related to the closing phase of the Acadian Orogeny (Ettensohn, 1994, 2004, 2005; Ettensohn and others, 2002). Basal transgressive parts of the sequence in the Sunbury and its equivalents reflect a final phase of active deformational loading, whereas overlying regressive parts from the Kinderhookian–Osagean Borden-Grainger-Pocono sequence to the largely Chesterian Paragon–Pennington–Mauch Chunk sequence represent succeeding phases of lithospheric relaxation. Moreover, the fact that the Mississippian section in eastern parts of the basin may be locally gradational with Pennsylvanian rocks suggests that Acadian relaxation continued into earliest Pennsylvanian time. Pennsylvanian relaxation was very short-lived, however, for both Pennsylvanian and Mississippian rocks were truncated on the major sub-Absaroka or "Mississippian-Pennsylvanian" unconformity, which apparently marks inception of the Alleghanian Orogeny.

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4: The Pennsylvanian of the Appalachian Basin

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Geologic Setting

Preserved Pennsylvanian strata in the Appalachian Basin reflect the development of three informally defined sub-basins. These sub-basins represent depocenters along the Appalachian trend. The northern Appalachian Basin includes Pennsylvania, Ohio, western Maryland, and the northern half of West Virginia, including that part of the bituminous coal fields in each state referred to as the Dunkard Basin. Several narrow basins east of the bituminous coal field in east-central Pennsylvania contain anthracite coals and can be considered part of the greater northern Appalachian Basin. The southern boundary of the northern Appalachian Basin is approximately the outcrop of the Conemaugh Formation (Fig. 4.1A), which divides the Northern and Southern West Virginia Coal Fields, and is the northern boundary of the Rome Trough, a basement aulocogen. Upper Middle and Upper Pennsylvanian strata are characteristically thick in the northern basin, whereas Lower Pennsylvanian strata are generally thin or absent. Exceptions are in the outlying anthracite fields where thick Lower Pennsylvanian strata are preserved. Total Pennsylvanian thickness in the bituminous coal field reaches 460 m in southwestern Pennsylvania, and exceeds 1,340 m in the anthracite fields (Edmunds and others, 1999).

The central Appalachian Basin (the southern part of which has also been referred to as the Pocahontas Basin) is located in the southern half of West Virginia, eastern Kentucky, southwestern Virginia, and the northern third of Tennessee (Fig. 4.1A). This sub-basin is located south of the Conemaugh subcrop. The southern limit is approximately defined at the limit of the Lower Pennsylvanian Pocahontas Formation and the Emery River Fault (Adams, 1984). Middle and Lower Pennsylvanian coal-bearing rocks and thick, Lower Pennsylvanian quartzose sandstones are the dominant strata preserved (Fig. 4.1B). Total Pennsylvanian thickness in the central Appalachian Basin reaches 1,524 m near the Kentucky-Tennessee line (Wanless, 1975).

The southern Appalachian Basin (as used herein) consists of the southern two-thirds of Tennessee and northernmost Alabama and Georgia to the northern limit of the Black Warrior Basin (Fig. 4.1A). The thin belt of Pennsylvanian strata in the southern Appalachian Basin is dominated by thick Lower Pennsylvanian quartzarenites with intervening units of shale, sandstone, and minor coal (Fig. 4.1B). These strata merge southward with the thick sequence of coal-bearing rocks in the Black Warrior Basin of Alabama. The Black Warrior

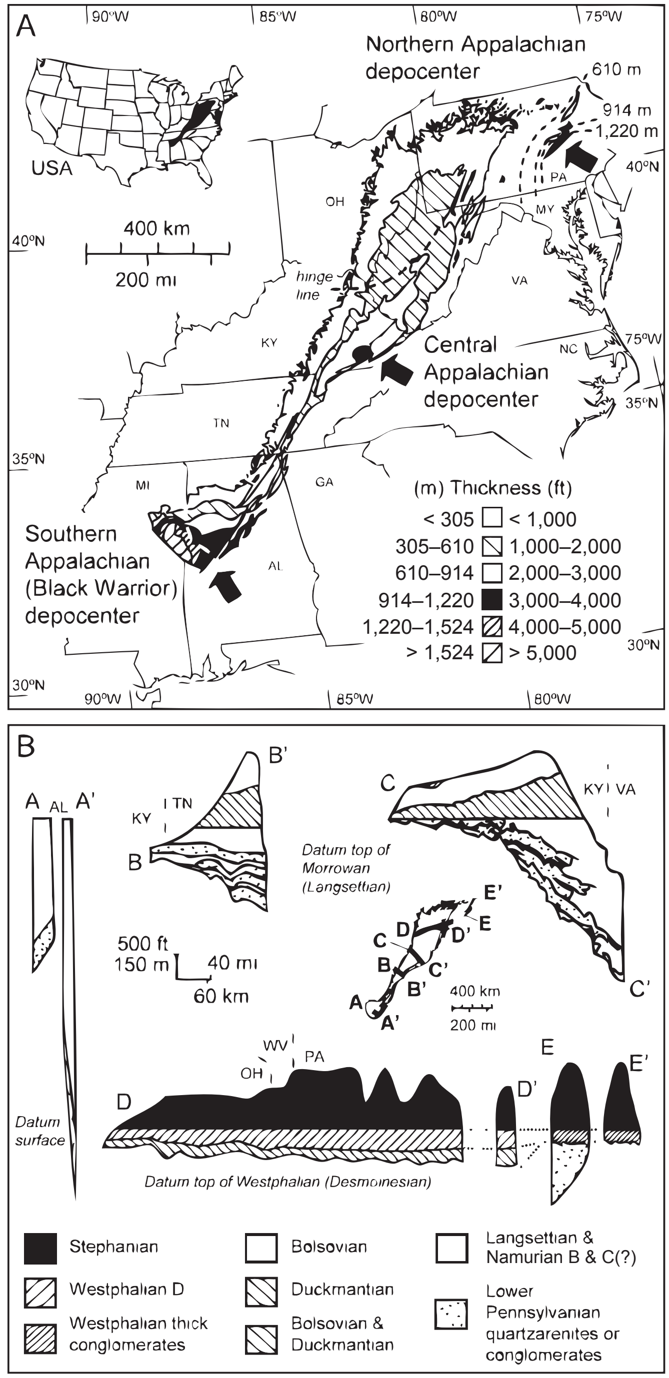

Figure 4.1. A. Isopach map of Pennsylvanian strata in the greater Appalachian Basin (after Wanless [1975]). B. Generalized cross sections across the basin. A–A′ after Wanless (1975); B–B′ and C–C′ after Chesnut (1992); D–D’ and E–E’ from Edmunds and others (1999) and Wanless (1975). From Greb and others (2008, Fig. 1). Reprinted with permission of Geological Society of America.

Basin, held to be part of the southern Appalachian Basin by some authors, is described herein as a separate basin (Pashin and Gastaldo, *this volume*). Total Pennsylvanian thickness in the southern Appalachian Basin reaches 550 m in southeastern Tennessee and Georgia (Wanless, 1975), but exceeds 2,500 m in the adjacent Black Warrior Basin (Pashin and Gastaldo, *this volume*).

Several small Pennsylvanian intermontane basins have been described in Maine, Massachusetts, and Rhode Island (Skehan and others, 1979), and are not generally regarded as part of the Appalachian Basin.

The Pennsylvanian Appalachian Basin was a foreland basin of much greater extent and volume than the present basin. The preserved basin is only part of the western limb of the original basin. The eastern limb and axial parts were destroyed by the Alleghanian Orogeny and by extensive post-Alleghanian erosion. Pennsylvanian strata within the preserved basin thicken to the east, into the preserved depocenters of the various sub-basins (Fig. 4.1A, B).

Lithostratigraphy

The Appalachian Basin is one of the world's largest Pennsylvanian coal-producing basins, with annual production of 375 to 425 million short tons. More than 34 billion short tons of coal have been mined in the past 200 years (Milici, 1999). Currently, the basin contains the second-, third-, and fourth-leading coal-producing states in the United States (West Virginia, Kentucky, and Pennsylvania, respectively). The long history of mining has led to a large amount of data for use in stratigraphic and other analyses. Extensive geologic and mine mapping has allowed for detailed rock-unit correlations within and between coal-mining states. Determination of equivalence to Lower, Middle, and Upper Pennsylvanian strata in other basins is mostly based on palynological analyses (discussed in Eble and others, *this volume).*

Each state in the Appalachian Basin has its own nomenclature for Pennsylvanian strata (Fig. 4.2). In general, states in the northern part of the basin use similar nomenclature. This is partly a function of very widespread, distinctive rock units that are easily traceable across multiple states. In contrast, Lower Pennsylvanian rock units are less persistent and the resulting nomenclature shows much greater variation, especially in the central and southern Appalachians (Fig. 4.2).

Mississippian-Pennsylvanian Boundary

The systemic boundary may be conformable in parts of the southern Appalachian Basin. It occurs within the upper Parkwood Formation in the Black Warrior Basin in Alabama (Smith, 1979; Pashin and Gastaldo, *this volume*) and has been interpreted as occurring in the Raccoon Mountain Formation and equivalents in the Gizzard Group of Georgia and southern Tennessee (Milici, 1974; Milici and others, 1979; Thomas and Cramer, 1979). Thick paleosols (Churnet, 1996) and paleokarst (Driese and others, 1998) in the uppermost Mississippian Pennington Formation beneath the Gizzard Group, and sequential truncation of underlying Pennington strata on the western outcrop margin of the southern Appalachian Basin (Hurd and Stapor, 1997), however, suggests that the contact is unconformable across most of Tennessee and possibly Georgia. In parts of east-central and westward on the basin margin in Tennessee, the Gizzard Group is missing and the Sewanee Conglomerate unconformably overlies the Upper Mississippian Pennington Shale (Milici and others, 1979; Churnet, 1996; Hurd and Stapor, 1997).

In the central Appalachian Basin the Mississippian-Pennsylvanian boundary is possibly conformable in the deepest part of the basin where the Pocahontas Formation overlies the Bluestone Formation (Arkle and others, 1979; Englund, 1979a, b; Milici and others, 1979), although that has recently been challenged (Blake and Beuthin, 2008). Previous interpretations of more widespread conformity based upon the perceived intertonguing of Lee Formation quartzose sandstones and underlying Mississippian marine units (Horne and others, 1971, 1974; Ferm, 1974) have been largely negated by research that recognizes (1) distinct Mississippian and Pennsylvanian quartzose sandstones and paleovalleys at the base of the Pennsylvanian, rather than a conformable intertonguing relationship, (2) truncation of Mississippian strata toward the basin margin, and (3) thick paleosols at the inferred unconformity (Rice and others, 1979; Ettensohn, 1980, 1994; Rice, 1984; Chesnut, 1988, 1989, 1992; Greb and Chesnut, 1996; Beuthin, 1997; Greb and others, 2002, 2004). Stratigraphic relationships suggest that the unconformity is Early Pennsylvanian (early Morrowan, mid-late Namurian) in age (Chesnut, 1992, 1994, 1996; Blake and Beuthin, 2008).

Throughout most of the northern Appalachian Basin, the Mississippian-Pennsylvanian contact is unconformable, becoming increasingly disconformable to the north and onto the western margins of the basin (Fig. 4.2). In northern Pennsylvania, Middle Pennsylvanian strata overlie uppermost Devonian strata (Edmunds and others, 1979, 1999). In the outlying anthracite fields, however, the Mississippian-Pennsylvanian boundary may be conformable where the Tumbling Run Member of the Pottsville Formation overlies the Mauch Chunk Formation. In fact, the systemic boundary may occur in the upper Mauch Chunk (Fig. 4.2), which is entirely Upper Mississippian to the south. The top of the Mauch Chunk is generally mapped at the uppermost occurrence of redbeds, which occur at a stratigraphically higher position in east-central Pennsylvania than to the south (Edmunds and others, 1999).

Lower Pennsylvanian

The Lower Pennsylvanian is traditionally equated to the Morrowan (North American regional stage) in the

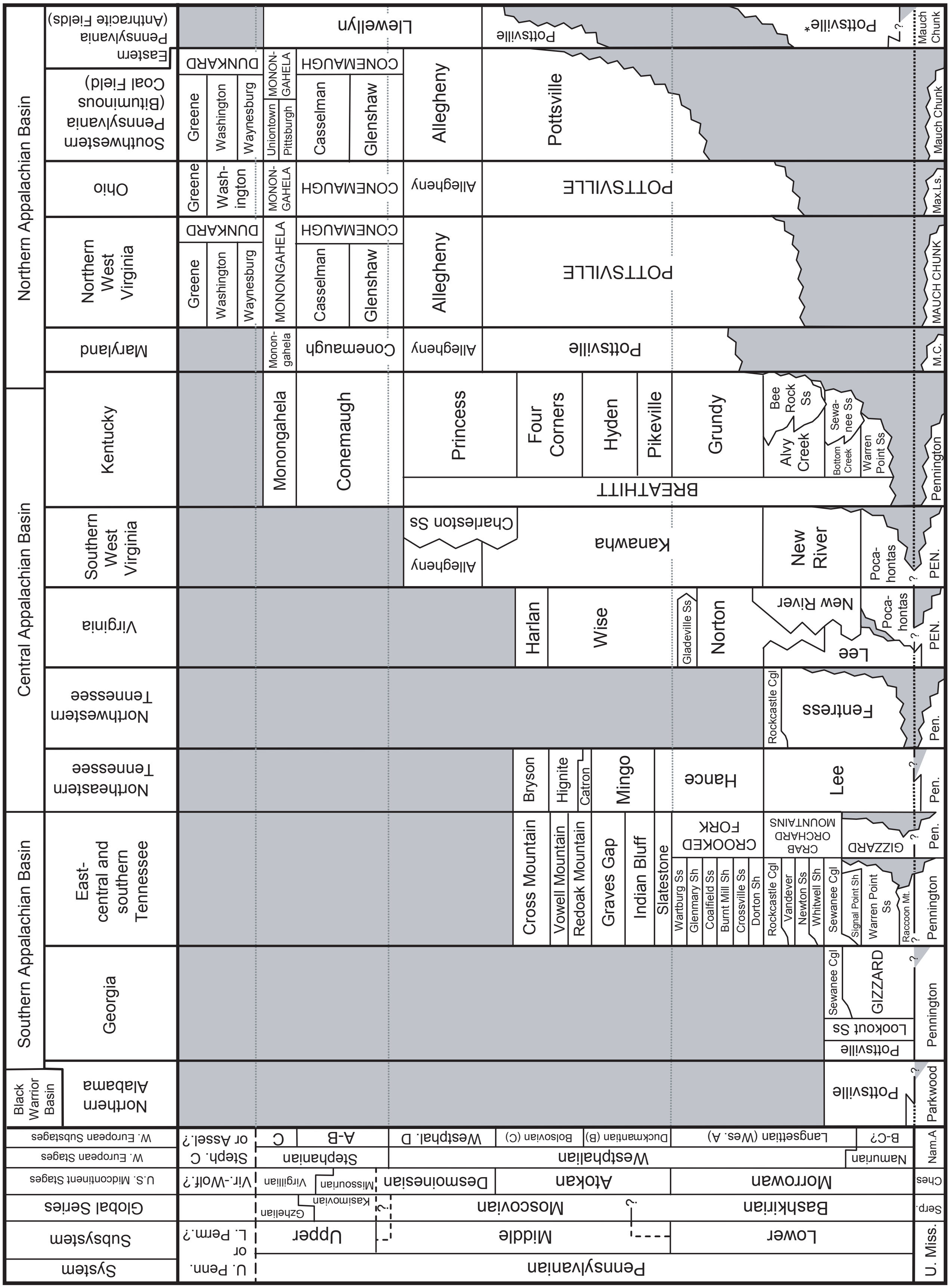

Figure 4.2. Correlation chart of major stratigraphic units of the Pennsylvanian rocks of the Appalachian Basin (state nomenclature modified from Patchen and others,1984a, b; Chesnut, 1992; Nolde, 1994; Edmunds and others, 1999). The Dunkard Group may be partly Lower Permian.

Appalachian Basin. Current international usage (Heckel and Clayton, 2006) would place the upper boundary of the Lower Pennsylvanian at the top of the Bashkirian global stage, which would be slightly younger and is uncertain in the basin (Fig. 4.2).

Lower Pennsylvanian strata are characterized by thick, quartz-pebble-bearing quartzose sandstones across much of the basin (Fig. 4.1B). Group, formation, and member boundaries are generally placed at the top and bottom of major sandstones. Because there is a series of sandstones with varying thickness and regional extent, the stratigraphy of the Lower Pennsylvanian between and sometimes within states also varies significantly (Fig. 4.2). Total preserved Lower Pennsylvanian thickness reaches 610 m in southern West Virginia (Wanless, 1975).

Lower Pennsylvanian strata in the southern Appalachian Basin consist of a series of alternating sandstone and shale formations (Fig. 4.2). The Gizzard Group thickens to the southeast toward the Black Warrior Basin (Churnet, 1996; Hurd and Stapor, 1997). The Warren Point Sandstone (30–91 m), Sewanee Conglomerate (24–61 m), Newton Sandstone (10–45 m), and Rockcastle Conglomerate (30–91 m) are thick, quartzose sandstones containing quartz pebbles. Each of the sandstones varies in thickness and may truncate and merge with underlying units (Milici and others, 1979; Churnet, 1996; Hurd and Stapor, 1997). Where the Warren Point and Sewanee are absent on the northwestern side of the Cumberland Plateau in Tennessee, Pennsylvanian strata beneath the Rockcastle Conglomerate are assigned to the Fentress Formation (Fig. 4.2). Most of the units between the various sandstone formations consist of gray silty shale, siltstone, sandstone (quartzose to subgraywacke), coal, and underclay. The Whitwell Shale contains most of the commercial coal beds in southern Tennessee, although the coals are generally thin and discontinuous (Milici and others, 1979).

Lower Pennsylvanian strata in the central Appalachian Basin consist of coal-bearing strata basinward in the Pocahontas (0–216 m), New River (0–314 m), and Norton (640 m) Formations (Fig. 4.2). These are replaced marginward by broad (greater than 60 km) belts of thick (greater than 30 m) quartzose sandstones mapped as members of the Lee Formation in northeastern Tennessee and Virginia; members of the Pottsville Group in southern West Virginia; and the Warren Point, Sewanee, and Bee Rock Sandstones, and members of the Grundy Formation in Kentucky (Miller, 1974; Arkle and others, 1979; Englund 1979a, b; Rice and others, 1979; Chesnut, 1992). Individual quartzose sandstones onlap the basin margins, sometimes truncating and merging with older sandstones (Fig. 4.1B) (Chesnut, 1992, 1994, 1996; Greb and others, 2002, 2004). Coal-bearing units consist of gray silty shale, siltstone, sandstone (quartzose to subgraywacke), coal, and underclay as in the southern basin, but coal beds are generally thicker and more continuous than to the south. The Pocahontas No. 3 coal bed (Pocahontas Formation) is the ninth-leading producer in the basin and ranked 17th in the United States in 2003, according to U.S. Energy Information Administration statistics.

Much of the Lower Pennsylvanian section thins into the northern Appalachian Basin and western basin margins (Fig. 4.1B). Eastward in the anthracite fields, the Lower Pennsylvanian thickens dramatically (Fig. 4.1B) where the Pottsville Formation contains the Tumbling Run (0–183 m) and Schuykill (0–213 m) members (Fig. 4.2). These units are dominated by conglomerate and sandstone, with lesser amounts of shale, siltstone, and coal. Coal beds are generally thin and discontinuous (Edmunds, 1999).

Middle Pennsylvanian

The Middle Pennsylvanian of the basin is traditionally based on the Atokan and Desmoinesian regional stages of North America, which have been equated to Westphalian B, C, and D stages of Europe. Current international usage equates the Middle Pennsylvanian to the Moscovian international stage. The lower boundary of the Moscovian is slightly younger than the base of the Atokan and the upper boundary may be slightly older than the top of the Desmoinesian (Heckel and Clayton, 2006).

Middle Pennsylvanian strata are absent in the southern part of the basin in Georgia and Alabama, but are well developed in the central and northern Appalachian Basins (Figs. 4.1B, 4.2). In Middle Pennsylvanian strata, quartzose sandstones are mostly absent. Most formations contain similar gray silty shales, micaceous to feldspathic sandstones, siltstones, coals, and underclays, although coal beds are more common and widespread than in the Lower Pennsylvanian. Formation boundaries are picked at prominent coal beds or extensive shale units. Because key beds vary across the basin, formations and formation boundaries are different in each state (Fig. 4.2), especially in the lower (pre-Allegheny Formation) part of the Middle Pennsylvanian. Total preserved Middle Pennsylvanian thickness exceeds 1,300 m along the Kentucky-Virginia state line (Wanless, 1975).

The Allegheny Formation was originally defined to encompass the mined coals of the northern Appalachian Basin. Because the coals that are economically mineable vary across the basin, the lower boundary varies between states, occurring stratigraphically higher in Pennsylvania than in Maryland and West Virginia (Fig. 4.2). The underlying Middle Pennsylvanian parts of the Pottsville contain few coal beds in the northern Appalachian Basin. In the central Appalachian Basin, however, the Kanawha Formation in West Virginia, Pikeville and Hyden Formations in Kentucky, and Wise and part of the Norton Formation in Virginia contain abundant coal beds.

In the central Appalachian Basin, the base of the Middle Pennsylvanian (Atokan, Duckmantian) is the Betsie Shale Member, a regionally widespread marine carbonaceous shale (Rice and others, 1987). Other Middle Pennsylvanian marine units that can be traced across the central Appalachian Basin include the Kendrick (Dingess) and Magoffin (Winifrede) Shale Members (Rice and others, 1979), each used by Chesnut (1992) as boundaries for Middle Pennsylvanian formations in Kentucky. Five to six coal zones are situated between each major marine zone (Chesnut, 1992, 1994). Coal beds generally thicken and split into zones of multiple beds toward the preserved basin axis (Wanless, 1975; Greb and others, 2002, 2004).

Some of the key coal beds in the Upper Pottsville–equivalent Middle Pennsylvanian coals include the third-, seventh-, eighth-, and 10th-leading producers in the basin (Upper Elkhorn No. 3 coal of Kentucky; Eagle coal, lower Kanawha Formation, of West Virginia and Kentucky; Pond Creek coal, Pikeville Formation, of Kentucky; Amburgy or Williamson coal, Hyden Formation, of Kentucky, respectively). These coals ranked seventh, 15th, 16th, and 19th, respectively, in the United States, according to U.S. Energy Information Administration statistics.

Allegheny-equivalent Middle Pennsylvanian coals include the second-, fourth-, fifth-, sixth-, and 11th-leading producers in the basin (Hazard No. 5 coal, Four Corners Formation, of Kentucky; Stockton coal, Allegheny Formation, of West Virginia; Lower Kittanning coal, Allegheny Formation, of West Virginia; Hazard No. 4 or Fire Clay coal, Four Corners Formation, of Kentucky; Upper Freeport, Allegheny Formation, of Pennsylvania, respectively). These coals ranked sixth, ninth, 10th, 12th, and 21st in production, respectively, in the United States, according to U.S. Energy Information Administration statistics.

Upper Pennsylvanian

The Upper Pennsylvanian of the basin has traditionally been equated to the Missourian and Virgillian regional stages of North America. Current international usage places the base of the Upper Pennsylvanian at the base of the Kasimovian global stage, which may be slightly older than the base of the Missourian (Heckel and Clayton, 2006).

Upper Pennsylvanian strata in the basin are absent in the southern and central parts of the basin. In the northern Appalachian Basin, Upper Pennsylvanian strata are represented by part of the Conemaugh, Monongahela, and Dunkard (at least the lower part) Groups/Formations. These units exhibit redbeds, pedogenic flint clays, and increased carbonates relative to Middle Pennsylvanian strata. Stratigraphic units also tend to be more persistent than in the Middle Pennsylvanian, so there is less variation in state nomenclature (Fig. 4.2). Total preserved Upper Pennsylvanian thickness exceeds 320 m in the anthracite fields of Pennsylvania (Wanless, 1975).

The Conemaugh Formation or Group was defined for a stratigraphic interval that contained few mineable coal beds, between the top of the Upper Freeport coal bed and the base of the Pittsburgh coal bed. The base of the Upper Pennsylvanian is placed in the lower part of the Conemaugh, in the Glenshaw Formation, below the Brush Creek coal bed (Blake and others, 2002). Above this interval are widespread, cyclic sequences containing red, gray, and green shales, caliche paleosols, carbonates, siltstones, and sandstone. Carbonates in the lower part of the group (Glenshaw Formation) may contain marine fossils, whereas the upper part (Casselman Formation) is nonmarine (Donaldson, 1974; Arkel and others, 1979; Collins, 1979; Donaldson and Shumaker, 1980; Martino, 1996b). The Brush Creek and Ames Limestones are the two most persistent limestones. The Conemaugh exceeds 250 m in thickness near the Maryland–West Virginia state line (Arkle and others, 1979).

The Monongahela Formation or Group is defined from the base of the Pittsburgh coal bed to the base of the Waynesburg coal bed. The Monongahela contains cyclic sequences of calcareous mudstones, shales, nonmarine limestones, sandstones, siltstones, and coal (Donaldson, 1974; Arkle and others, 1979; Collins, 1979; Donaldson and Shumaker, 1980; Edmunds, 1999). Limestones and coals thin and disappear to the southwest (Arkle and others, 1979). The Monongahela reaches a maximum thickness of 120 m in northern West Virginia (Arkle and others, 1979).

The Pittsburgh coal bed, at the base of the Monongahela, is one of the most widespread coals in the world, covering more than 21,000 km^2, with an estimated original resource of 34 billion short tons. It has produced approximately 18 billion short tons, more than any other coal bed in the United States (Ruppert, 2002). The coal remains the leading producer in the basin (second in the United States), with 77 million short tons mined in 2003, according to U.S. Energy Information Administration statistics.

Pennsylvanian-Permian

The Dunkard Group contains all of the upper Paleozoic strata above the Waynesburg coal bed. In southeastern Pennsylvania, the Dunkard Group is entirely nonmarine, although some units may be correlative to marine units to the west (Heckel, 1995). The Dunkard is similar in lithology to the underlying Monongahela but contains fewer and thinner coal beds. It thickens to 335 m in southwestern Pennsylvania and adjacent parts of northern West Virginia (Arkle and others, 1979; Edmunds and others, 1979; Edmunds, 1999).

The age of the Dunkard Group is uncertain. Fossil flora in the Dunkard are mostly transitional between Upper Pennsylvanian and Lower Permian flora. Read and Mamay (1964) placed the boundary within the

Dunkard, but subsequent studies of flora (Gillespie and others, 1975) and palynology (Clendening, 1975) place all of the Dunkard in the Upper Pennsylvanian. The U.S. Geological Survey and most state surveys in the northern basin map the Waynesburg Formation as Upper Pennsylvanian–Permian and the Greene Formation as Permian.

Depositional History

Early Pennsylvanian

During the Pennsylvanian, the Appalachian Basin was between 5 and 20° south of the equator and tilted clockwise 35 to 45° from its present position (Scotese, 1994). The basin drifted northward from drier climatic belts in the Mississippian to wetter belts (e.g., Intertropical Convergence Zone) during the Pennsylvanian (Cecil and others, 1994). Reconstructions of basin-scale depositional systems at different times in the Pennsylvanian can be found in Donaldson and Shumaker (1980), Donaldson and others (1985), and Chesnut (1994). Maps of selected coal beds can be found in Appalachian Basin Resource Assessment Team (2002).

Areas of possible conformity between the Mississippian and Pennsylvanian Systems in the southern and deepest central basin correspond to depocenters in which subsidence had begun in the Late Mississippian. Earliest Pennsylvanian sediment in the southern (Raccoon Mountain) and central (Pocahontas) depocenters was deposited in a wide range of coastal-deltaic environments (Arkle and others, 1979; Englund, 1979a, b; Milici and others, 1979). In the anthracite fields of the northern Appalachian Basin, Early Pennsylvanian sedimentation was dominated by coarse alluvial fans and rivers prograding from highlands to the southeast, with additional clastic contribution from lowlands to the north of the basin (Pedlow, 1979; Edmunds and others, 1999).

The quartz-pebble-bearing sandstones that dominate much of the Early Pennsylvanian have been interpreted as barrier islands, tidal channels, tidal straits, and fluvial systems (discussed in Greb and Chesnut, 1996), but most appear to have been formed in large south-flowing braided streams in broad braidplains oriented parallel to the rising highlands (Archer and Greb, 1995; Churnet, 1996; Greb and Chesnut, 1996; Hurd and Stapor, 1997). Paleotopography on the underlying sub-Absaroka surface and local structural controls influenced sedimentation in several parts of the basin (Edmunds and others, 1979, 1999; Horne, 1979; Padgett and Ehrlich, 1979; Churnet, 1996; Greb and Chesnut, 1996). Progressive expansion of clastic wedges building westward from the Appalachian highlands during the Lower Pennsylvanian led to westward migration of the quartzose river system through time (Chesnut, 1994, 1996). Paleovalleys were cut during lowstands, and channels within the fluvial systems were locally converted to estuaries during periodic transgressions from the south (Greb and Chesnut, 1996; Greb and Martino, 2005). Marine incursions became more pronounced toward the late Early Pennsylvanian (Chesnut, 1991), extending as far north as Pennsylvania (Edmunds, 1992).

During the Early Pennsylvanian, peats accumulated on interfluves and coastal plains developed on the clastic wedges that built out into the central Appalachian (Pocahontas) Basin. Everwet conditions prevailed, which promoted the formation of ombrogenous (rainfall-fed) mires. Coals that formed from these peats, such as the Pocahontas No. 3, tend to be low in ash and sulfur, as is typical of many Lower and Middle Pennsylvanian mined seams in the central Appalachian Basin (Cecil and others, 1985; Cecil, 1990; Eble, 1996b).

Middle Pennsylvanian

In the Middle Pennsylvanian, the longitudinal braidplain ceased to exist and coal-bearing coastal plains with generally west-flowing rivers became widespread across much of the central basin. Sedimentation onlapped and buried sub-Absaroka paleotopography in the northern part of the basin by the mid-Atokan (Edmunds and others, 1999). Marine incursions became more common and widespread, depositing dark gray, carbonaceous shales (Williams, 1979; Chesnut, 1991). Shale members of the Kanawha Formation and Breathitt Group such as the Betsie, Kendrick (Dingess), and Magoffin (Winifrede) were originally interpreted as bay fills in deltaic models (e.g., Horne and others, 1971) but have since been interpreted as seaways open to the southeast (Chesnut, 1989; Martino, 1996a).

The marine-to-marine zone cycle (major transgressive-regressive cycle) has been interpreted as a tectonic cycle (Tankard, 1986) and a glacial-eustatic cycle (Chesnut, 1994, 1997; Heckel, 1995). Coal-to-coal cycles are generally attributed to glacial eustasy (Chesnut, 1991, 1992, 1994; Donaldson and Eble, 1991). Sequence-stratigraphic divisions of the section have interpreted the coal-to-coal cycles as third- or fourth-order sequences (Chesnut, 1994; Aitken and Flint, 1994, 1995; Greb and others, 2004). Most recently, new absolute dates in the Appalachian Basin (Lyons and others, 1992; Outerbridge and Lyons, 2006) have been used to infer that the coal-to-coal cycle (minor transgressive-regressive cycle) had an average duration of 0.1 million years, which supports the hypothesis of short eccentricity–driven eustatic influences on sedimentation (Greb and others, 2008).

Everwet climates persisted and widespread peats formed in response to fluctuating sea levels. Based on mapping, mining, and the presence of an extensive tonstein in the Hazard No. 4 (Fire Clay) coal, the major-resource coal beds were originally formed as extensive basinwide peat mires locally interspersed with west-flowing rivers. Low sulfur and ash yields in many of the mined coals have been used to infer ombrogenous mire origins where the coals are thick (Esterle and Ferm, 1986; Eble, 1994, 1996a), although there were also vast areas of lateral planar mires (Eble and Grady, 1993; Greb and others, 2002).

Late Pennsylvanian

Upper Pennsylvanian strata are missing from the central and southern Appalachian Basin, but the overall coarsening-upward trend in the coal-bearing strata from the mid-Early to Late Pennsylvanian and accompanying loss of marine conditions in the northern basin is commonly interpreted as reflecting continued progradation of clastic wedges from the Appalachian highlands, resulting in a transition from dominantly coastal-delta plain to alluvial plain environments of deposition (Ferm, 1970, 1974; Donaldson, 1974; Arkle and others, 1979; Edmunds and others, 1979; Chesnut, 1992). Following the retreat of marine conditions from the basin by the Virgillian, the northern basin remained a lacustrine flood basin. Rivers flowed into the lacustrine basin from the Appalachian highlands to the south and southeast, as well as from the stable craton to the north (Berryhill and others, 1971; Donaldson, 1974; Wanless, 1975; Edmunds and others, 1979, 1999; Donaldson and Shumaker, 1980; Donaldson and others, 1985).

The onset of wet-dry seasonality resulted in increased lacustrine carbonate deposition and the development of red vertic soils. Climatic controls also may have resulted in a shift from ombrogenous to planar, rheotrophic mires, leading to the high-sulfur and -ash coals typical of the northern Appalachian Basin (Cecil and others, 1985; Cecil, 1990).

Biostratigraphic Framework

Palynology has been the principal means of biostratigraphic correlation for Pennsylvanian strata in the basin and is summarized in Eble and others *(this volume).* Information on other taxa that have been correlated within the basin are also summarized in the papers in this volume. Some additional pertinent biostratigraphic research in the basin that is not covered in this volume includes Middle and Upper Pennsylvanian fusulinid correlations between the Illinois Basin and central and northern Appalachians by Douglas (1969, 1987) and Smyth (1974). These correlations support palynologic and lithostratigraphic correlations between the two basins. In addition, Upper Pennsylvanian conodonts have been found in the Brush Creek Limestone (*bc* in Fig. 4.3) through Ames Limestone (*a* in Fig. 4.3) interval of the Conemaugh Group in the northern Appalachian Basin. These have been correlated to conodonts in limestones and deep-water shales in the Illinois Basin and Midcontinent by Heckel (1994, 1995, 2007). These correlations seem to agree well with existing palynological and lithostratigraphic correlations. Heckel used existing palynological and lithostratigraphic correlations of strata as old as the Lower Kittanning coal *(lk* in Fig. 4.3) of the Allegheny Formation/Group (upper Desmoinesian stage of North America) to coals and depositional cycles in the Illinois Basin, and then correlated conodonts from roof shales in those coals to upper Desmoinesian marine shales in the Midcontinent.

Radiometric Dating

Tonsteins derived from volcanic ashfalls occur in several of the coal beds within the basin (Burger and Damberger, 1979; Bohor and Triplehorn, 1981, 1984; Chesnut, 1985; Outerbridge and others, 1990). Two have yielded grains that can be radiometrically dated: the tonstein associated with the Fire Clay coal (Lyons and others, 1992; Rice and others, 1994; Kunk and Rice, 1994) and a tonstein found locally in the Upper Banner coal.

Sanidines from a tonstein in the Fire Clay coal of eastern Kentucky (*f* in Fig. 4.3) and West Virginia have been dated at 310 ±0.8 Ma (Rice and others, 1994), 311 ±1 Ma (Hess and Lipolt, 1986), and 312 ±1 Ma (Lyons and others, 1992) using $^{40}Ar/^{39}Ar$ techniques. The coal is in the SF microfloral zone (see Eble and others, *this volume),* and a 310 to 312 Ma age corresponds relatively well with a Middle Pennsylvanian stratigraphic position based on palynomorphs in recent time scales (Fig. 4.3). Internationally, the Lower–Middle Pennsylvanian boundary is the Bashkirian-Moscovian stage boundary, which is slightly younger than the top of the Morrowan (North American stage) or Langsettian (western Europe stage), which are used to define the Lower Pennsylvanian in this basin. Currently, the Bashkirian-Moscovian stage boundary is estimated to be 311.7 Ma (Fig. 4.3) (Gradstein and others, 2004). A tonstein dated at 310 to 312 Ma would be within or close to the lower part of the Middle Pennsylvanian as suggested by biostratigraphy and lithostratigraphy.

Recent U-Pb analyses of zircons from the same tonstein, however, have yielded a slightly older date, 314.6 ±0.9 Ma (Outerbridge and Lyons, 2006). A 314 Ma date would be Early Pennsylvanian in age, regardless of whether the top of the Morrowan, Langsettian, or Bashkirian is used to designate the Lower Pennsylvanian, or whether the Gradstein and others (2004) or Menning and others (2006) time scale was used. It is also older than would be inferred from correlations of palynomorphs to international time scales (Fig. 4.3). The older age for the same tonstein indicates a discrepancy between U-Pb and $^{40}Ar/^{39}Ar$ dating methods for Carboniferous rocks that needs to be investigated. U-Pb rather than $^{40}Ar/^{39}Ar$ dating methods are used, however, for the international time scale (e.g., Gradstein and others, 2004).

Radiometric dating of a sanidine from the Upper Banner coal of the Norton Formation of Virginia using U-Pb analyses indicates a 316.1 ±0.8 Ma date (Outerbridge and Lyons, 2006), which would also be in the Lower Pennsylvanian *(ub* in Fig. 4.3). The Upper Banner is in the SR microfloral zone, which has been inferred to be upper Lower Pennsylvanian. Hence, although the date is 2 to 3 million years older than would

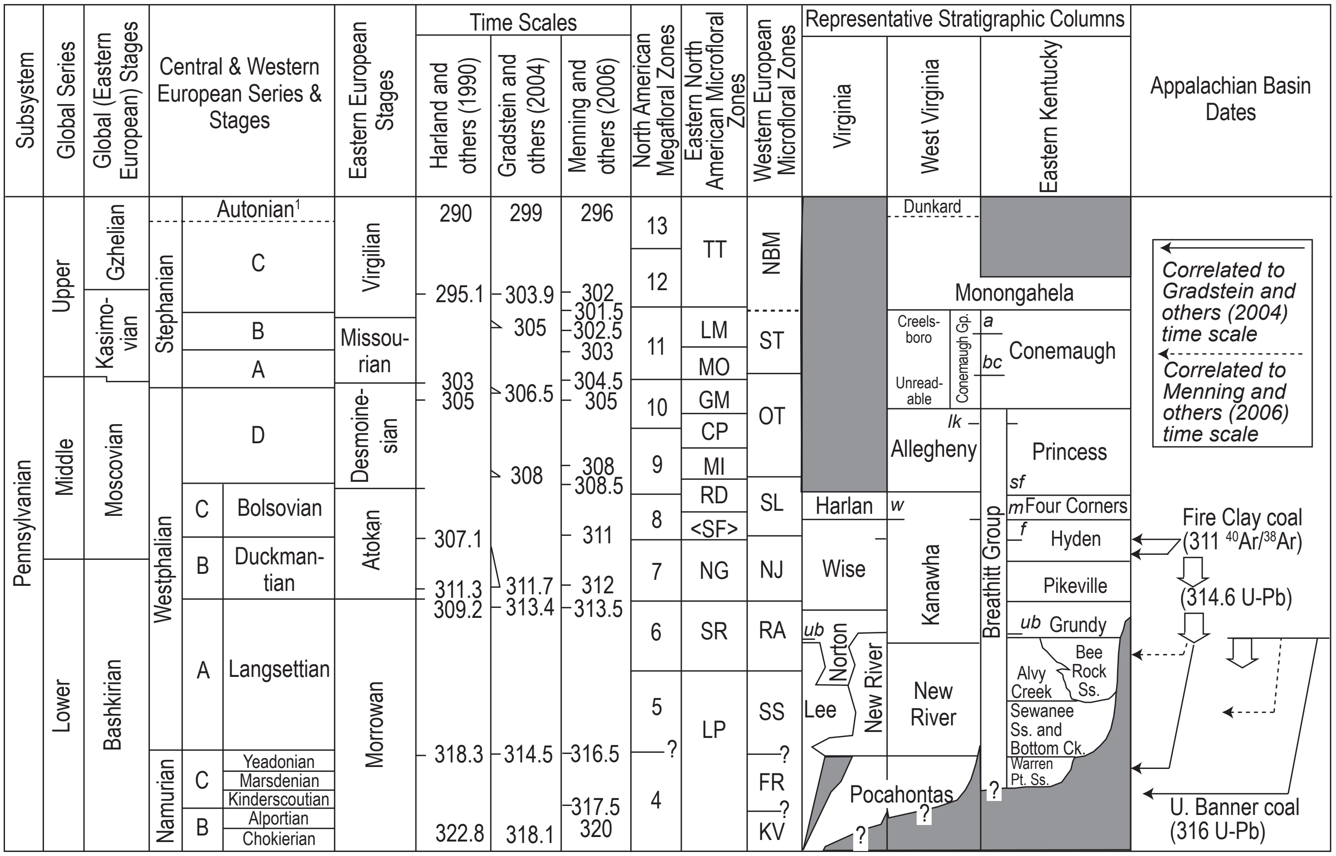

Figure 4.3. Potential changes to correlations of central Appalachian Basin strata to international series and stages as a result of the new absolute dates from the Fire Clay and Upper Banner coals reported by Outerbridge and Lyons (2006). Note that there are differences in Lower Pennsylvanian stages between the most recent time scales that influence potential correlations of the new dates. North American megafloral zones from Read and Mamay (1964), eastern North American microfloral zones from Peppers (1996), western European microfloral zones from Clayton and others (1977), and correlations between zones based on Blake and others (2002) and Eble and others *(this volume)*. Microfloral zone SF is shown in its position for the Illinois Basin, but may be younger in the Appalachian Basin. The Dunkard Group may be partly Lower Permian.

have been inferred based on palynoflora, it is still Early Pennsylvanian (and Bashkirian) in age (Fig. 4.3**)**.

An interesting aspect of the two new dates is that if further research substantiates them, then much of the strata currently assigned to the Middle Pennsylvanian of North American usage in the central Appalachian Basin would be moved into the Lower Pennsylvanian of international usage. Outerbridge and Lyons (2006) used a regression from their two U-Pb dates to infer an age of 314.4 Ma for the Magoffin Shale (*m* in Fig. 4.3), and 313.6 Ma for the Stoney Fork Member *(sf* in Fig. 4.3) of the Breathitt Group in Kentucky (and equivalents in West Virginia). The Magoffin is currently considered Middle Pennsylvanian (middle Atokan stage of North America; upper Duckmantian/Westphalian B substage of western Europe) and the Stoney Fork as upper Middle Pennsylvanian (upper Atokan stage of North American; middle Bolsovian/Westphalian C substage of western Europe) based on palynomorphs. The new projected dates would drop both units into the Lower Pennsylvanian (Bashkirian of international usage; Westphalian A/Langsettian substage of western Europe), which is substantially different than indicated by biostratigraphic (e.g., Eble and others, *this volume*; Work and others, *this volume*) and lithostratigraphic data. Furthermore, if current biostratigraphic correlations based on conodonts for the Upper Pennsylvanian (Missourian and Virgillian stages of North America) and perhaps as old as the upper Middle Pennsylvanian (Desmoinesian stage of North America) are correct (e.g., Heckel, 2007), this would have the effect of leaving a relatively thin interval of strata between approximately the Lower Kittanning coal *(lk* in Fig. 4.3) of the Allegheny Formation/Group and the Stoney Fork Member of the Princess Formation, as representing the Middle Pennsylvanian (Moscovian stage of international usage) in the central Appalachian Basin. Several paleosols in this interval could represent more time than is currently thought, but more synthesis of existing biostratigraphic, lithostratigraphic, and radiometric data is obviously needed to resolve these issues.

The new U-Pb dates do not change the existing lithostratigraphy or biostratigraphy within the Appalachian Basin, nor do they change the correlations to nearby basins (Illinois and Midcontinent Basins), which are based on North American stages; they only affect the correlation of these strata to other international basins and the potential placement of what is called "Lower" and "Middle" Pennsylvanian in the future relative to the international standard.

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5: Appalachian Basin Fossil Floras

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Late Paleozoic Megafloral Biozonations

During the early and middle part of the 20th century, numerous zonation schemes have been advanced for various Carboniferous basins in the central and western European part of the paralic coal belt (e.g., Dix, 1937). Read and Mamay (1964) have advanced the only megaflora-based zonation for Carboniferous and Permian strata in North America. Several problems detract from the utility of their zonation, the most serious of which is the lack of accompanying range charts. As stated, their zones are actually characteristic assemblages and not biozones. Wagner (1984) introduced a comprehensive megafloral biozonation for the entire Amerosinian Floral Realm, synthesizing data from many sources. Accompanying the biozones were range charts addressing numerous taxa. Most recently, Blake and others (2002) have presented a detailed discussion of Appalachian plant biostratigraphy. This paper is essentially an abstract of that effort.

Proposed Pennsylvanian System Stratotype (pPSs)

During the 1970's, the U.S. Geological Survey established a composite reference section for Pennsylvanian strata in southern West Virginia and southwestern Virginia. This area was chosen because the Pennsylvanian section had been widely reported as being the most continuous in North America. This composite section was nominated as the stratotype for the Pennsylvanian System, but the International Stratigraphic Code (Salvador, 1994) requires boundary stratotypes rather than unit stratotypes, and the paucity of marine strata containing goniatites and other biostratigraphically significant marine taxa (i.e., conodonts, fusulinids) has largely curtailed its acceptance. Nonetheless, the component sections represent the most complete sequence of predominantly terrestrial Pennsylvanian strata in North America, and the large amount of lithostratigraphic and biostratigraphic data generated during the course of the pPSs study make these sections invaluable for local, transcontinental, and intercontinental biostratigraphic correlations (Englund and others, 1979).

While field work was conducted related to the establishment of the pPSs (1975–80), plant megafossils were collected from several hundred localities. These data resulted in a preliminary megaflora-based correlation between North American and western and central European sections (Gillespie and Pfefferkorn, 1979). More recent collecting and stratigraphic research in the area (Blake, 1992, 1997, 1998, 1999; Blake and Gillespie, 1994; Gillespie and others, 1999) have amended and strengthened many of the preliminary conclusions. Additional studies (Englund and others, 1985; Gillespie and Crawford, 1985; Gillespie and Rheams, 1985; Cross and others, 1996) have used these preliminary results to correlate strata of various areas in North America with the pPSs.

Devonian–Early Carboniferous

The Devonian-Carboniferous systemic boundary is characterized biostratigraphically by the extinction of the latest Devonian (Famennian) *Archaeopteris-Rhacophyton-Elkinsia* floras and the beginning of the *Lepidodendropsis* floras of the lowermost Mississippian Price Formation (Scheckler, 1986). Basal Mississippian (Tournaisian) strata have been divided into two megafloral zones by Read and Mamay (1964) that correspond roughly to the Kinderhookian and Osagean of the Eastern Interior region. The oldest megafloral zone (zone 1) recognized by Read and Mamay is the zone of *Adiantites* spp., and is characterized by abundant *Adiantites spectabilis*, less common *Rhodeopteridian, Alcicorneopteris,* and *Lagenospermum,* and uncommon *Lepidodendropsis* (Fig. 5.1). Megafloral zone 2, the zone of *Triphyllopteris* spp., is found in the Price Formation and extends into the Maccrady Formation. After reevaluating European material, Knaus (1994) transferred North American specimens previously assigned to the form genus *Triphyllopteris* to the new form genus *Genselia* Knaus and Gillespie.

Middle Mississippian megafloras in the Appalachian region are poorly known because this part of the section is occupied by the marine Greenbrier Limestone and regional correlatives. Read and Mamay's megafloral zone 3, the zone of *Fryopsis abbensis* (Read) Wolfe, occurs in the lower part of the Bluefield Formation and the lower part of the Hinton Formation (Fig. 5.1). It contains a diverse megaflora similar in composition to the lower Namurian (Upper Pendleian to Lower Arnsbergian) of western and central Europe (Jongmans and Gothan, 1937). Wagner (1994) has assigned *Fryopsis* to *Cardiopteridium*. This Upper Mississippian zone occurs from the base of the Bluestone Formation upward into the Hinton Formation and contains a different and diverse megaflora nearly identical in composition to the lower Namurian megaflora (upper Pendleian to lower Arnsbergian) of western and central Europe (Jongmans and Gothan, 1937). On the basis of European floral successions, Read and Mamay (1964) predicted, but were

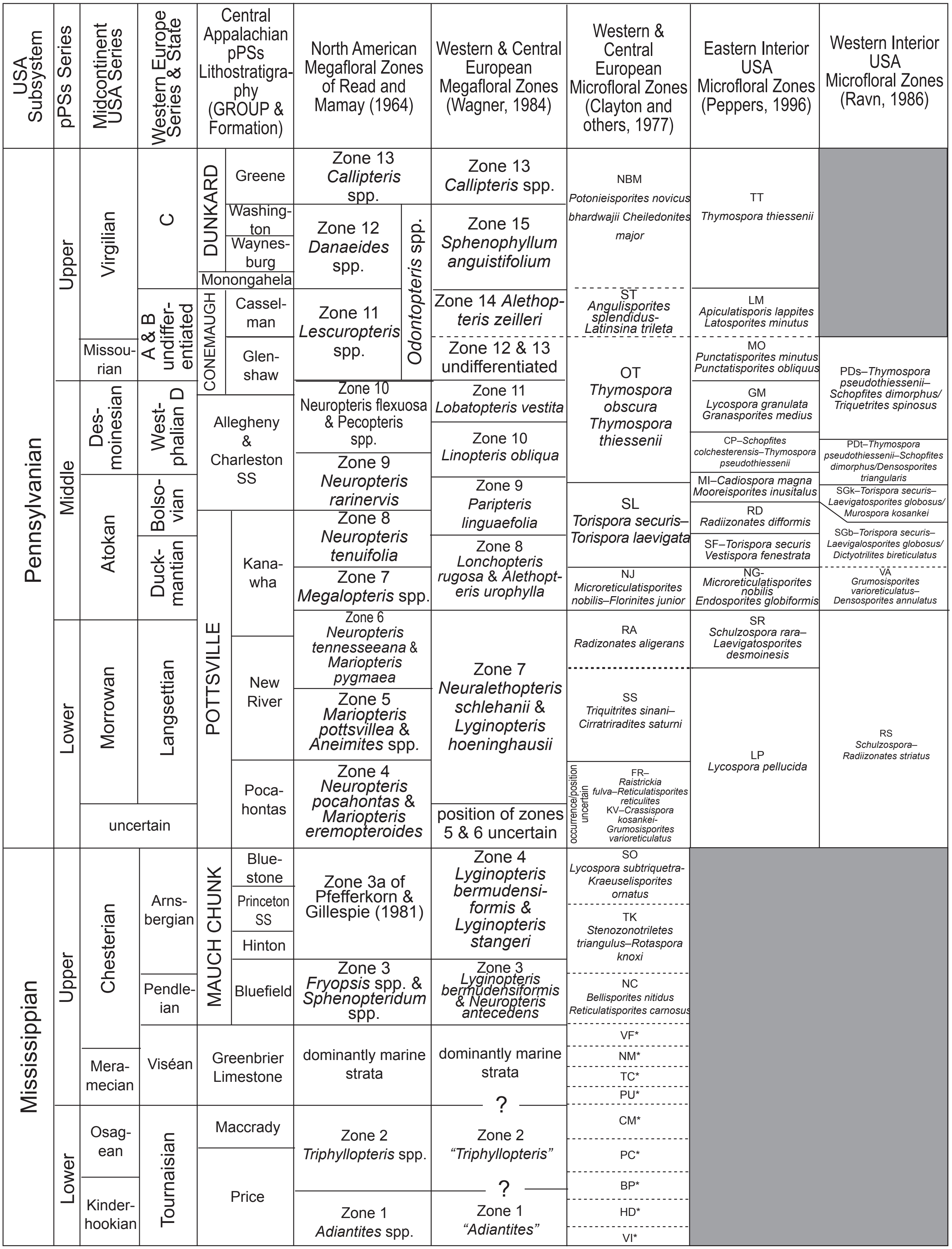

Figure 5.1. Correlation chart of central Appalachian stratigraphic units with North American and European Carboniferous floral zones. *See Table 5.1 for key to Mississippian microfloral zones.

Table 5.1. Mississippian microfloral zones for western and central Europe.

(VF)	*Tripartites vetustus–Rotaspora fracta*
(NM)	*Raistrickia nigra–Triquitrites marginatus*
(TC)	*Perotriletes tesseliatus–Schulzospora campyloptera*
(PU)	*Lycospora pusilla*
(CM)	*Schopfites claviger, Auroraspora macra*
(PC)	*Spelaeotriletes pretiosus–Raistrickia clavata*
(BP)	*Spelaeotriletes balteatus–Rugospora polyptycha*
(HD)	*Krauselisporites hibernicus–Umbonatisporites distinctus*
(VI)	*Vallatisporites vallatus–Retusotriletes incohatus*

Tournasian miospore zones are from Higgs and others (1988).

unable to confirm, the presence of a megafloral zone between their zones 3 and 4. Gillespie and Pfefferkorn (1979) recognized and characterized this lower Namurian (ex-Namurian A) megafloral zone, which they named "zone 3A" (Pfefferkorn and Gillespie, 1981, 1982). This zone correlates with the *Lyginopteris bermudensiformis–Lyginopteris stangerii* biozone and possibly the lower part of the *Lyginopteris larischii* biozone of Wagner (1984), both of which correlate with the Upper Mississippian (lower Namurian) E_2 goniatite zone.

The late Arnsbergian megaflora found at the base of the Pride Shale is essentially the same as the megaflora reported by Jennings and Thomas (1987) from the lower part of the Parkwood Formation of Alabama. The presence of the latest Mississippian conodont *Gnathodus postbilineatus* near the top of the marine Bramwell Member (Bluestone Formation) indicates a latest Arnsbergian (earliest Chokierian?) age (R.G. Stamm, U.S. Geological Survey, Reston, Va., written communication, 1995). The presence of *Gnathodus postbilineatus*, the precursor to the earliest Pennsylvanian *Declinognathodus noduliferus* zone, suggests a position very close to the Mid-Carboniferous boundary. Brachiopods (Henry and Gordon, 1992) and bivalves (Hoare, 1993) indicate a Chesterian (Late Mississippian) age for the Hinton and Bluefield Formations.

Pennsylvanian System

Pocahontas Formation

Read and Mamay (1964) placed the Pocahontas Formation megaflora in zone 5, the zone of *Neuropteris pocahontas* and *Mariopteris eremopteroides* (now *Sphenopteris pottsvillea*). The presence of *Lyginopteris hoeninghausii* would suggest a placement of strata overlying the Pocahontas No. 3 coal bed in Wagner's (1984) *Neuralethopteris schlehanii-Lyginopteris hoeninghausii* biozone, which virtually corresponds with the Langsettian Stage. At this time, the age of the lower part of the Pocahontas Formation is uncertain (Figs. 5.2–5.3).

New River Formation

Read and Mamay (1964) placed the lower part of the New River Formation in the zone of *Mariopteris pottsvillea* and *Aneimites* spp., and the upper part in zone 6, the zone of *Neuropteris tennesseeanea* (sic) and *Mariopteris pygmea*. New River Formation megafloras belong to the *Neuralethopteris schlehanii-Lyginopteris hoeninghausii* biozone of Wagner (1984), indicating a Langsettian age (Figs. 5.1–5.2).

Kanawha Formation

The sub-Betsie Shale Member paleoflora consists primarily of holdovers from the underlying New River Formation (Fig. 5.2).The extinction of *Karinopteris acuta*, *Lyginopteris hoeninghausii*, and *Neuralethopteris schlehanii* in this interval indicates a position in the upper part of the *Lyginopteris hoeninghausii–Neuralethopteris schlehanii* biozone of Wagner (1984), and a late Langsettian age assignment.

Initially, the paleoflora found between the Betsie Shale Member and the Winifrede Shale Member (Figs. 5.2–5.3) contains the same elements found below the Betsie Shale Member with the loss of *Karinopteris acuta*, *Lyginopteris hoeninghausii*, and *Neuralethopteris* spp. New taxa are gradually introduced just above the Dingess Shale Member.

A significant change, first noted by David White (1900), occurs in the megaflora above the Winifrede Shale Member (Figs. 5.2–5.3), with several plant taxa originating or terminating near the top of the Kanawha. This paleoflora compares with the upper part of the European Bolsovian Stage and is assigned to the *Paripteris linguaefolia* biozone of Wagner (1984) (Fig. 5.2).

Read and Mamay's (1964) megafloral zonation for this interval contains problems and contradictions. The lower part of the Kanawha Formation was placed in megafloral zone 7, the zone of *Megalopteris* spp., and they correlated this assemblage with the lower part of the Atokan Series of the North American Midcontinent (Fig. 5.1). Biostratigraphically significant species listed for zone 7 include Bolsovian (late Kanawha) and younger forms, however. Read and Mamay (1964) further considered zone 8, the zone of *Neuropteris tenuifolia* (Fig. 5.1), as characteristic of the majority of the Kanawha Formation, citing a previously published megaflora list with outdated taxonomy (White, 1900) from the roof shales of the Eagle coal. The Eagle coal bed is clearly older than the Bolsovian assemblage listed as characteristic of zone 7, however. As such, Read and Mamay's zone 7 is actually younger than zone 8, which until recently was an unrecognized problem that has hampered biostratigraphic work in North America. In addition, *Megalopteris* is an extrabasinal plant (Leary and Pfefferkorn, 1977), atypical of the wet costal plain paleomire floras. It also ranges from the late Namurian to the middle Westphalian.

Charleston Sandstone and Allegheny Formation

Most early work in the Appalachian Basin equated the Charleston Sandstone of central and southern West Virginia (Campbell and Mendenhall, 1896) with the Allegheny Formation of more northern areas, a practice continued in the pPSs (Arndt, 1979). There are major differences between the two units, however. The lower part of the Charleston Sandstone is very thick, with numerous economic coal beds, whereas the upper part is rather thin, and coal beds, where present, are thin as well and few in number. The situation is reversed in the Allegheny Formation, with thick, economic coals occurring in the upper part, and the lower part being thin with few coal beds.

Read and Mamay (1964) placed the lower part of the Allegheny Formation (and, by default, the lower part of the Charleston Sandstone) in zone 9, the zone of *Neuropteris rarinervis*. They placed the upper part of the Allegheny Formation and lower part of the overlying Conemaugh Group in zone 10, the zone of *Neuropteris fleuxosa* and *Pecopteris* spp. The main part of the Charleston Sandstone (Upper No. 5 Block coal and below; see Fig. 5.2), which lithologically is a continuation of the underlying Kanawha Formation, correlates with the upper part of the *Paripteris linguaefolia* and the lower part of the *Linopteris obliqua* biozone of Wagner (1984). The lower part of the Allegheny Formation correlates with the *Linopteris obliqua* biozone of Wagner (1984). The main part of the Allegheny Formation (above the Clarion coal bed) is assignable to the *Lobatopteris vestita* biozone (Wagner, 1984). Wagner and Lyons (1997) suggested, however, that the interval from just above the Upper Kittanning coal to the top of the Upper Freeport coal could be placed in the *Odontopteris cantabrica* biozone (Wagner, 1984) (see Fig. 5.2).

Conemaugh Group

In the northern part of the Appalachian region, formation contacts were historically placed at the level of economically important coal beds, with little regard for lithologic continuity. The Allegheny Formation–Conemaugh Group contact is placed at the top of the Upper Freeport coal bed (Fig. 5.2), even though lowermost Conemaugh strata (top of Freeport coal to just below the Brush Creek coal; see Fig. 5.2) are lithologically indistinguishable from subjacent Allegheny strata. Conemaugh strata above this interval are strikingly different, however, with the section being dominated by red and green shales, mudstones, and paleosols, the latter with features suggestive of development under dry climatic conditions (Cecil and others, 1994; Joeckel, 1995).

The roof shale megafloras of the Upper Freeport and Mahoning coals are indistinguishable from late Allegheny paleofloras. Read and Mamay (1964) placed the upper part of the Allegheny Formation and the lower part of the Conemaugh Group in zone 10, the zone of *Neuropteris flexuosa* and *Pecopteris* spp., a position high in the Desmoinesian Series of the Midcontinent region (Figs. 5.1–5.2). This megaflora also indicates a position near the Westphalian-Stephanian boundary. Wagner and Lyons (1997) pointed out, however, that the co-occurrence of *Mariopteris nervosa* and *Sphenophyllum oblongifolium* in the roof shales of the Upper Freeport suggests a basal Stephanian age assignment.

Read and Mamay (1964) placed the majority of the Conemaugh Group (above the Brush Creek coal) and the lower part of the overlying Monongahela Formation in their megafloral zone 11, the zone of *Lescuropteris* spp. In addition, they stated their megafloral zone 11 was inseparable from the overlying megafloral zone 12, zone of *Danaeides* spp. in many areas (Fig. 5.1).

Monongahela Group

Monongahela megafloras are primarily known from the Pittsburgh coal bed (Fig. 5.2). The first occurrences of *Sphenophyllum angustifolium* and *S. thonii* in the roof shales over the Pittsburgh coal bed (Fig. 5.2) suggest a correlation with the base of the *Sphenophyllum angustifolium* biozone of Wagner (1984). This biozone marks the Stephanian B-C boundary in western and central Europe (Wagner, 1984) (Figs. 5.1–5.3).

Dunkard Group

The Dunkard megaflora was originally discussed in a monograph by Fontaine and White (1880). It is essentially a continuation of the underlying Monongahela megaflora, but also contains elements characteristic of older formations (Fig. 5.1). The age of the Dunkard Group has been widely debated since publication of Fontaine and White's (1880) monograph. Generally, the Dunkard has been considered transitional Pennsylvanian-Permian in age, with the Waynesburg and Washington Formations being assigned a Pennsylvanian age and the Greene Formation being considered Permian. The Permian assignment was based primarily on the presence of *Callipteris (Auntunia*), including *C. conferta,* in the Greene Formation, which the first two Heerlen congresses had adopted as an indicator of Permian age (Jongmans and Gothan, 1937). This conclusion has since been invalidated, however, with the report of *Autunia conferta* in the Stephanian C of Europe (Havlena, 1970).

The sporadic appearance of *Autunia conferta* above the Washington coal bed suggests a correlation with a level high in the European Stephanian C or perhaps even lower Autunian, according to Wagner (1984), who placed these strata in his *Callipteris* (*Autunia*) *conferta* biozone. Recently, Wagner and Lyons (1997) have suggested the Greene Formation correlates with the lower Rotliegendes of western Europe (Figs. 5.1–5.2).

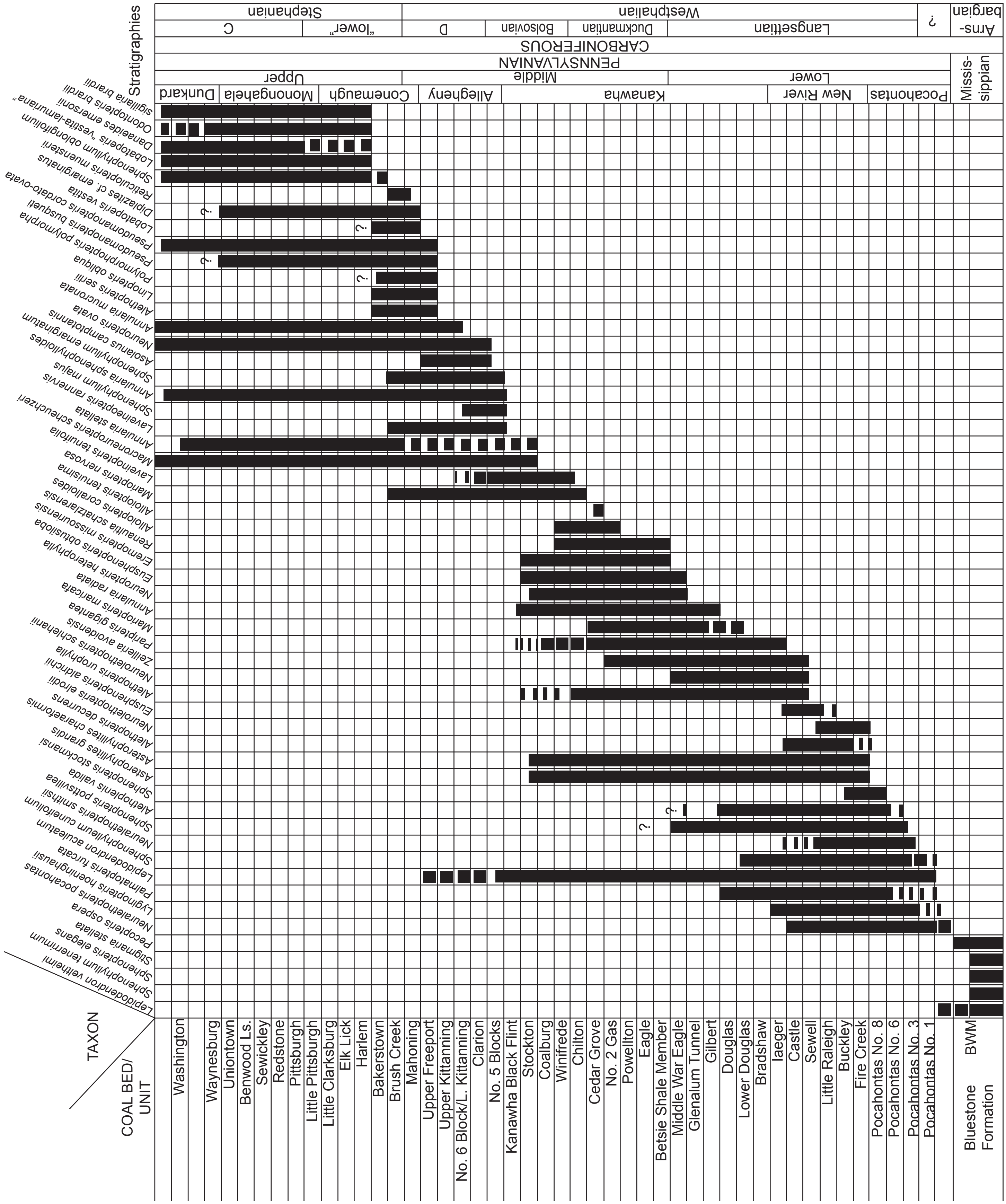

Figure 5.2. Stratigraphic range of important Pennsylvanian plants of the Appalachian Basin. Continued on next page. All macroflora identifications are from shale beds that occur below, within (separating coal benches), or above the coal beds listed. Bars that partially cover blocks reflect how high above or below a particular coal the taxa was identified.

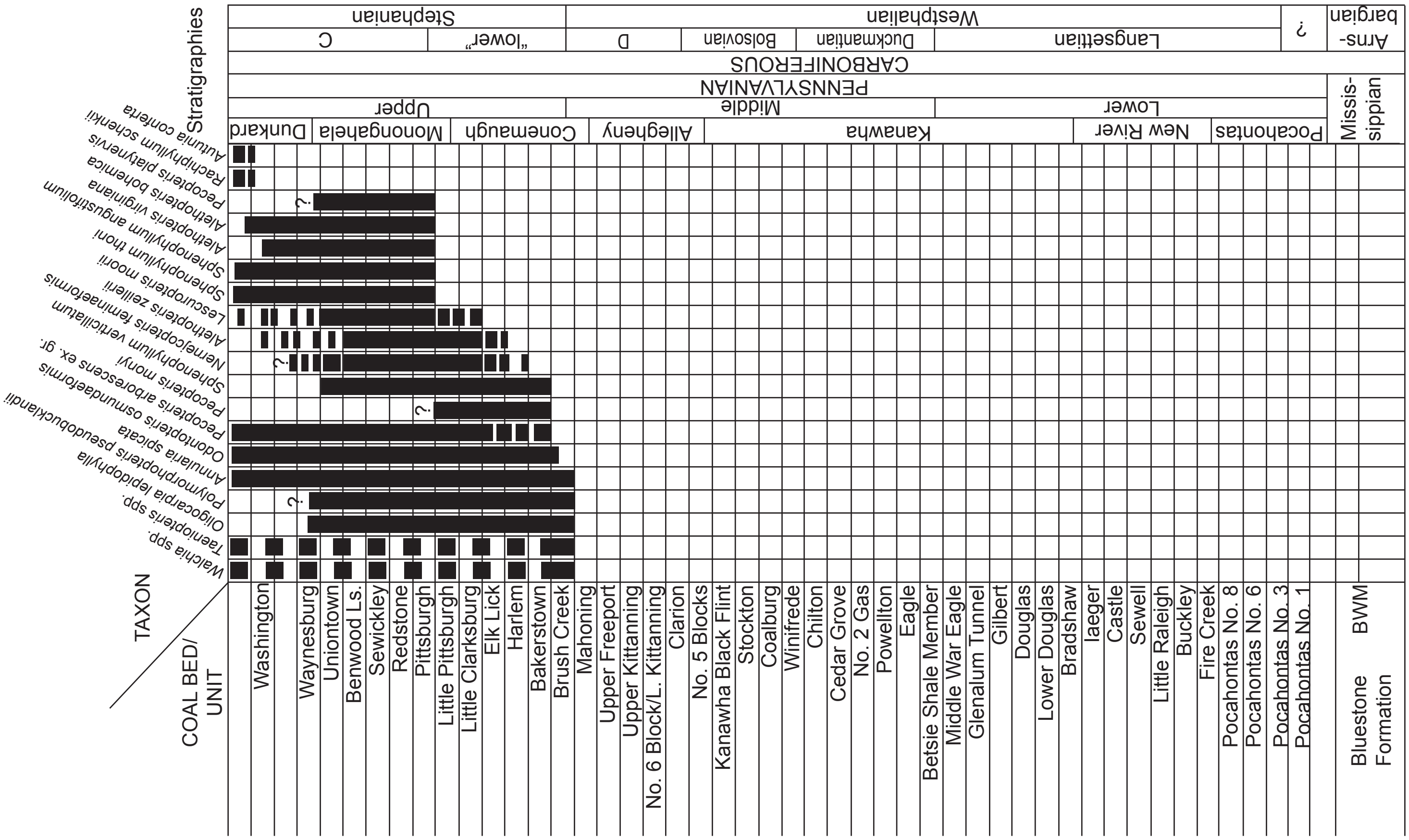

Figure 5.2. Continued from previous page. See caption on previous page.

Late Paleozoic Microfloral Biozonations

Palynological work in the pPSs has primarily been limited to strata above the level of the Sewell coal bed (New River Formation; see Fig. 5.2); older coal beds are too high in rank for meaningful palynomorph recovery. As such, all of our palynologic knowledge of pre-Sewell (Mississippian and Early Pennsylvanian) strata in the Appalachian Basin comes from areas adjacent to the pPSs. Although a palynomorph assemblage zonation has not been constructed for the Appalachian Basin, several studies in the stratotype area have been conducted (Kosanke, 1984, 1988a–c; Kosanke and Cecil, 1996). Others (e.g., Eble, 1994, 1996a, b) have drawn comparison with zonations from other areas, most notably the U.S. Midcontinent basins (Peppers, 1985, 1996; Ravn, 1986) and western Europe (Smith and Butterworth, 1967; Clayton and others, 1977).

Devonian/Mississippian

Winslow (1962) and Eames (1974) examined palynomorphs of Late Devonian and Early Mississippian strata in Ohio. These authors considered the Sunbury Shale, which occurs at the base of the Cuyahoga Group, to mark the base of the Carboniferous. Englund (1979) has correlated the Sunbury Shale with the Big Stone Gap Member of the pPSs. In adjacent Pennsylvania, Streel and Traverse (1978) placed the Devonian-Carboniferous boundary in the lower part of the Pocono Formation, which is a correlative of the Price Formation in the pPSs (Englund, 1979). Collectively, these data agree with the megafossil evidence and indicate the base of the Carboniferous should be placed at or near the base of the Big Stone Gap Member. In western Europe, the Devonian-Carboniferous boundary is placed between two palynological subzones, the *Spelaeotriletes lepidophytus–Verrucosisporites nitidus* (LN) below and the *Vallatisporites vallatus–Retusotriletes incohatus* (VI) subzones above (Clayton and others, 1977) (Fig. 5.1).

The mid-Mississippian Greenbrier Limestone represents a gap in the Appalachian palynologic succession, as it has not been possible to obtain palynomorphs from this extensive marine unit. Strata from the top of the Newman Limestone (the Greenbrier Limestone equivalent in Kentucky) to the base of the Pennsylvanian System have been examined for palynomorphs, however. Ettensohn and Peppers (1979) studied Late Mississippian shales and coals from northeastern Kentucky and determined that the strata were of late Viséan and early Namurian age. Late Mississippian strata from southeastern Kentucky have been examined as well (Chesnut and Eble, 2000), with similar findings. All samples from the top of the Newman Limestone to

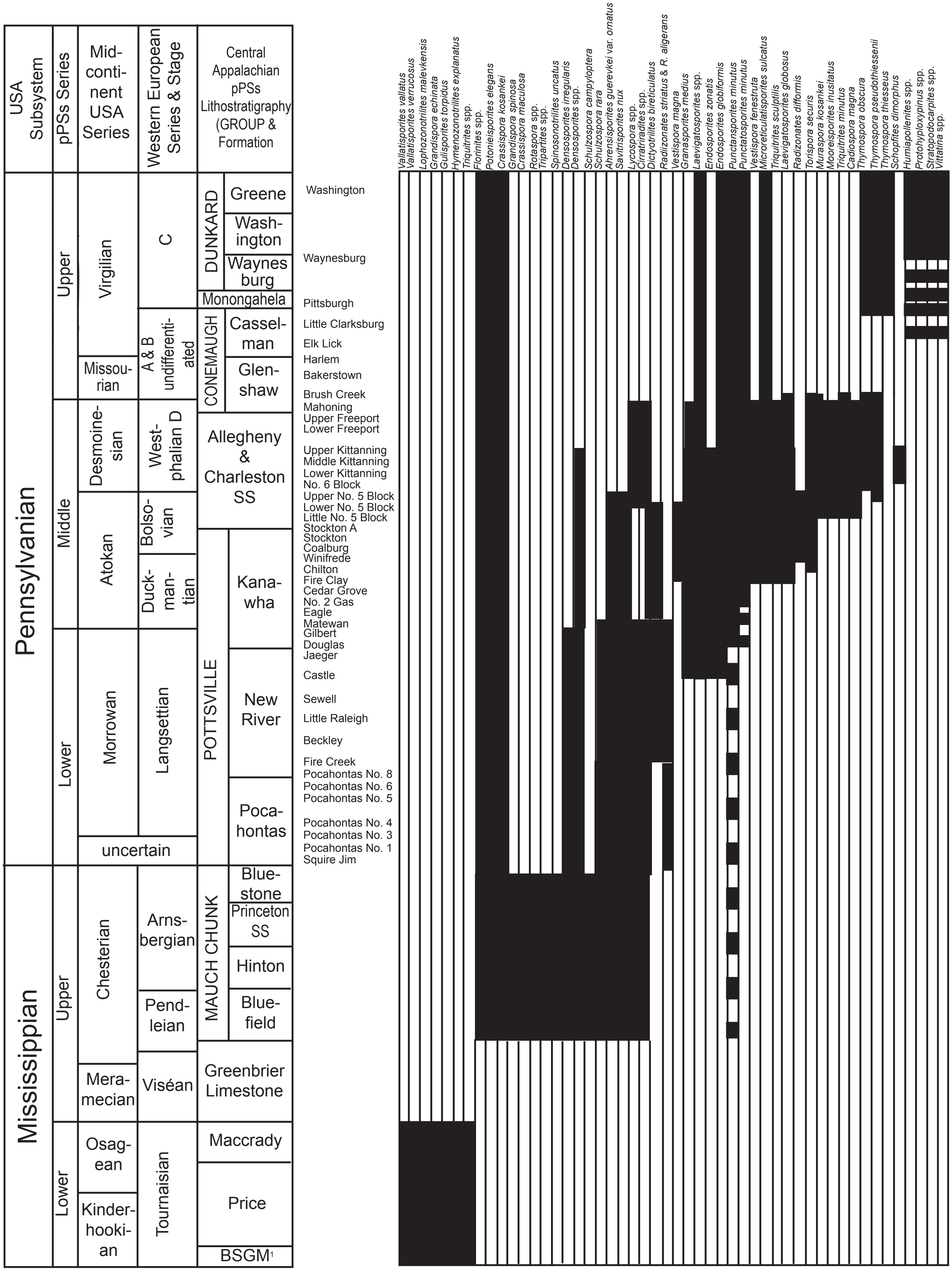

Figure 5.3. Correlation chart of Pennsylvanian rocks of the Appalachian Basin compared with western Europe and the Midcontinent region of the United States. Important marine strata (bold) and coal beds of the central part of the basin are shown in the right column.

the base of the Pennsylvanian best correlate with the *Bellisporites nitidus–Reticulatisporites carnosus* (NC) and *Stenozonotriletes triangulus–Rotaspora knoxi* (TK) miospore assemblage zones of western Europe (Clayton and others, 1977). Because the uppermost part of the Viséan is palynologically indistinguishable from the lowermost part of the Namurian (Clayton and others, 1977), however, assemblages from strata directly above the Newman Limestone may be correlative with the *Tripartites vetustus–Rotaspora fracta* (VF) zone (Fig. 5.1).

To date, an assemblage that correlates with the youngest Namurian assemblage zone in western Europe, the *Lycospora subtriquetra–Kraeuselisporites ornatus* (SO) zone, has yet to be identified in the central Appalachians. This probably indicates that the Late Mississippian section west of the stratotype area is truncated, a concept supported by lithostratigraphic analysis (Chesnut, 1992). Assemblages recovered from some coal samples near the top of the Parkwood Formation in the southern Appalachians did correlate with the SO assemblage zone, however, indicating the presence of a more complete Late Mississippian section in that area (Eble and others, 1991).

Pennsylvanian System

Pocahontas Formation. Pocahontas Formation palynomorphs are only known from an overthrusted area in southwestern Virginia, where coal rank remains in the high-volatile range (Eble, 1996b). Pocahontas assemblages best correlate with the *Lycospora pellucida* (LP) assemblage zone of the Eastern Interior Basin (Peppers, 1996) and the *Schulzospora rara–Radiizonates striatus* assemblage zone of the Western Interior Basin (Ravn, 1986). Although historically regarded as being Namurian B/C in age (e.g., Gillespie and Pfefferkorn, 1979), the presence of *Radiizonates* in Pocahontas coals suggests that at least some part of the Pocahontas Formation may actually be Langsettian in age, a notion supported by megafloral indices (Figs. 5.2–5.3).

New River Formation. Coal beds below the level of the Castle coal (Figs. 5.1, 5.3) contain palynofloras very similar to those of the Pocahontas Formation. Other forms seen above this level serve to differentiate coals in the bottom half of the New River Formation from coals in the top half. Strata below the level of the Castle coal bed best conform with the *Lycospora pellucida* (LP) assemblage zone of the Eastern Interior Basin (Peppers, 1996), whereas strata above the Castle correlate with the *Schulzospora rara–Laevigatosporites desmoinensis* (SR) assemblage zone. New River assemblages also correlate with the *Schulzospora rara–Radiizonates striatus* assemblage zone of the Western Interior Basin (Ravn, 1986) and the *Triquitrites sinani–Cirratriradites saturni* (SS) and *Radiizonates aligerans* (RA) assemblage zones (western Europe) (Clayton and others, 1977). Collectively, a Langsettian age is indicated for the entire New River Formation (Fig. 5.1).

Coal beds of the Black Warrior Basin in the southern Appalachians have been analyzed (Eble and others, 1985, 1991; Eble and Gillespie, 1989) and are correlative with New River coals. The introduction of *Endosporites*, *Granasporites medius,* and *Laevigatosporites* at the level of the Guide coal is similar to the introduction of these genera just above the Castle coal of the pPSs.

Kanawha Formation. Palynofloras from the lower part of the Kanawha Formation (pre-Betsie Shale Member) are similar to those observed in the underlying New River Formation, with assemblages from the lower part of the Kanawha Formation conforming with the upper part of the *Radiizonates aligerans* (RA) assemblage zone (Clayton and others, 1977). Lower Kanawha assemblages also correlate with the upper part of the *Schulzospora rara–Laevigatosporites desmoinensis* (SR) assemblage zone of the Eastern Interior Basin (Peppers, 1996) and the *Schulzospora rara–Radiizonates striatus* (RS) assemblage zone of the Western Interior Basin (Ravn, 1986) (Fig. 5.1).

Palynomorph assemblages in coal beds between the Betsie Shale and Dingess Shale (Fig. 5.3) correlate with the *Microreticulatisporites nobilis–Florinites junior* (NJ) assemblage zone of western Europe, the *Microreticulatisporites nobilis–Endosporites globiformis* (NG) zone of the Eastern Interior Basin (Peppers, 1996), and the *Grumosisporites varioreticulatus–Densosporites annulatus* (VA) zone of the Western Interior Basin (Ravn, 1986) (Fig. 5.3).

Strata between the Dingess Shale and the Winifrede Shale correlate with the lower part of the *Torispora securis–Torispora laevigata* (SL) assemblage zone of western Europe (Clayton and others, 1977), the *Torispora securis–Vestispora fenestrata* zone of the Eastern Interior Basin (Peppers, 1996), and the *Torispora secures–Laevigatosporites globosus/Dictyotriletes bireticulatus* (SGb) subzone of the Western Interior Basin (Ravn, 1986) (Fig. 5.3).

Spore and pollen assemblages in the upper part of the Kanawha Formation are extremely diverse, with every major Pennsylvanian plant group being represented by numerous species. The upper part of the Kanawha Formation correlates with the middle-upper part of the *Torispora securis–Torispora laevigata* (SL) assemblage zone of western Europe (Clayton and others, 1977), the *Radiizonates difformis* (RD) zone of the Eastern Interior Basin (Peppers, 1996), and the *Torispora secures–Laevigatosporites globosus/Dictyotriletes bireticulatus* (SGb) subzone of the Western Interior Basin (Ravn, 1986) (Fig. 5.3).

Charleston Sandstone: Allegheny Formation. Palynologically, coal beds in the Charleston Sandstone are similar in composition to those of the Upper Kanawha Formation. Charleston Sandstone strata between the top of the Kanawha Formation and the base of the Little

No. 5 Block coal correlate with the *Radiizonates difformis* (RD) miospore assemblage zone of the Eastern Interior Basin (Peppers, 1985, 1996), the *Torispora securis–Laevigatosporites globosus/Dictyotriletes bireticulatus* miospore subzone of the Western Interior Basin (Ravn, 1986), and the top of the *Torispora secures–Torispora laevigata* assemblage zone of western Europe (Clayton and others, 1977) (Fig. 5.3).

Strata from the Little No. 5 Block coal to the Lower No. 5 Block coal correlate with the *Cadiospora magna–Mooreisporites inusitatus* assemblage zone of the Eastern Interior Basin (Peppers, 1985, 1996), the *Torispora securis–Laevigatosporites globosus/Murospora kosankei* subzone of the Western Interior Basin (Ravn, 1986), and the bottom part of the *Thymospora thiessenii–Thymospora obscura* (OT) assemblage zone of western Europe (Clayton and others, 1977) (Fig. 5.3).

The next coals in succession, the Upper No. 5 Block and No. 6 Block coals, correlate with the *Schopfites colchesterensis–Thymospora pseudothiessenii* (CP) assemblage zone of the Eastern Interior Basin (Peppers, 1985, 1996), the *Thymospora pseudothiessenii–Schopfites dimorphus*/*Densosporites triangularis* (PDt) miospore subzone of the Western Interior Basin (Ravn, 1986), and the middle part of the *Thymospora thiessenii–Thymospora obscura* (OT) assemblage zone of western Europe (Clayton and others, 1977) (Fig. 5.3).

Based on a limited number of samples, coal beds above the No. 6 Block coal (No. 7–9? Block) are provisionally correlated with the *Lycospora granulata–Granasporites medius* (GM) assemblage zone of the Eastern Interior Basin (Peppers, 1985, 1996), the *Thymospora pseudothiessenii–Schopfites dimorphus*/*Triquitrites spinosus* (PDs) miospore subzone of the Western Interior Basin (Ravn, 1986), and the top of the *Thymospora thiessenii–Thymospora obscura* (OT) assemblage zone of western Europe (Clayton and others, 1977) (Fig. 5.3).

Palynologic correlation of lower Allegheny Formation coals in northern West Virginia, western Pennsylvania, and northeastern Ohio with areas to the south is somewhat problematic. The range of *Thymospora pseudothiessenii* extends down to the level of the Upper Mercer coal, well below the Lower Kittanning in northern areas, while to the south *Thymospora pseudothiessenii* is first seen immediately below the No. 6 Block, the Lower Kittanning equivalent. Another difference is that lower Allegheny Formation coals in the northern area completely lack *Radiizonates,* which ranges up to the level of the Upper No. 5 Block coal in central and southern West Virginia. Collectively, these disparities make the Lower Allegheny coals of northern West Virginia, western Pennsylvania, and northeastern Ohio appear "younger" than their southern counterparts, an observation that was noted earlier by Schemel (1957).

Conemaugh Group. The basal part of the Conemaugh Group, from the Upper Freeport to the Brush Creek coal bed and overlying marine zone (Fig. 5.1), is lithologically indistinguishable from the subjacent Allegheny Formation. Above this interval, Conemaugh strata are strikingly different, the section being dominated by red and green shales, mudstones, and paleosols, the latter with features suggestive of development under relatively dry to seasonally dry climatic conditions (Cecil and others, 1994; Joeckel, 1995).

The Mahoning coal correlates with the top of the *Lycospora granulata–Granasporites medius* (GM) assemblage zone in the Eastern Interior Basin (Peppers, 1985, 1996), the top of the *Thymospora pseudothiessenii–Schopfites dimorphus* (PD) assemblage zone in the Western Interior Basin (Ravn, 1986), and the top of the *Thymospora thiessenii–Thymospora obscura* (OT) zone in western Europe (Clayton and others, 1977). In contrast, the overlying Brush Creek coal correlates with the *Punctatisporites minutus–Punctatisporites obliquus* (MO) assemblage zone in the Eastern Interior Basin (Peppers, 1985, 1996) and the *Thymospora thiessenii–Thymospora obscura* (OT) zone in western Europe (Clayton and others, 1977). There is no correlative assemblage zone for Brush Creek and younger palynofloras in the Western Interior Basin (Fig. 5.3).

Palynomorph assemblages from the top of the Brush Creek coal to the base of the Little Clarksburg coal (Fig. 5.3) correlate with the *Punctatisporites minutus–Punctatisporites obliquus* (MO) and *Apiculatasporites lappites–Latosporites minutus* (LM) miospore assemblage zones of the Eastern Interior Basin (Peppers, 1996). A correlative assemblage zone for the Western Interior Basin has not yet been identified. They are also tentatively correlated with the *Angulisporites splendidus–Latensina trileta* (ST) assemblage zone of western Europe (Clayton and others, 1977) (Figs. 5.1, 5.3). Miospore correlation of Late Pennsylvanian strata with western European spore assemblage zonations is difficult because several stratigraphically important taxa, including *Lycospora, Densosporites,* and *Torispora*, all end their ranges near the Middle–Late Pennsylvanian boundary. All of these genera continue into the Stephanian in western European basins, however. In addition, several European index genera (e.g., *Angulisporites, Lundbladispora, Latensina,* and *Candidispora)* are either extremely rare or absent in the Appalachians. Part of this problem is the fact that European assemblage zones are derived from the analysis of both coal and clastics, whereas Appalachian palynofloras are known almost exclusively from coal. The paralic nature of Late Pennsylvanian sediments in the Appalachians, versus mainly limnic nature of Stephanian sediments in western European basins, is probably an important factor as well.

Monongahela Group. The Pittsburgh coal bed (Figs. 5.1, 5.3), which marks the base of the Monongahela Group, represents the epibole of *Thymospora thiessenii* in the Appalachian Basin. Other Monongahela Group coals, such as the Redstone, Sewickley, and Waynesburg (Fig. 5.1), contain several species of *Thymospora* but typically aren't as monospecific.

Monongahela assemblages correlate with the *Thymospora thiessenii* (TT) miospore assemblage of the Eastern Interior Basin (Peppers, 1985, 1996) and are tentatively correlated with the NBM assemblage zone of western Europe (Clayton and others, 1977) for the same reasons listed above for the Conemaugh Group. A correlative assemblage zone for the Western Interior Basin has not yet been identified (Fig. 5.3).

Dunkard Group. Dunkard Group coal and clastic palynofloras were studied extensively by Clendening (1970, 1972, 1974, 1975) and Clendening and Gillespie (1972). Overall, Dunkard assemblages closely resemble the late Conemaugh and Monongahela Group spore floras just discussed and are more indicative of a Pennsylvanian, not Permian, age, which agrees with the plant megafossil data. Interbasinal correlations are the same as those identified for the underlying Monongahela Group.

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6: Mississippian Conodonts of the Appalachian Basin

John E. Repetski and Robert Stamm

Despite the relatively thick Lower Carboniferous succession in the Appalachians, strikingly little work has been published on its conodonts and their biostratigraphy, particularly when contrasted with the excellent record developed in central and western North America. This is due in part to the predominance of siliciclastic strata through the interval in the Appalachian Basin, compared to the more extensive occurrence of marine carbonate rocks in central and western parts of the continent. The summary herein is based on these few published works and on unpublished data from U.S. Geological Survey collections, a few unpublished theses, and other ongoing work known to us.

The lower part of the conodont zonation used herein (Fig. 6.1) is based on those of Sandberg and others (1978) and Lane and others (1980). The upper part, from upper Meramecian through Chesterian, is that developed by Collinson and others (1971) for the Mississippi River Valley region, but is modified here due to the work of Stamm in his regional study of Appalachian faunas and their correlation westward into the Illinois Basin.

Kinderhookian conodonts are known only from the western edge of the Appalachian Basin, from condensed sections of shales. Hass (1947) reported *Siphonodella*-bearing faunas from the basal part of the Orangeville Shale in northern Ohio and from the Sunbury Shale in south-central Ohio. Hass (1956) also documented that much of the Maury Formation in Tennessee is Kinderhookian. Recent work by Mason, Work, and Sandberg in northeastern Kentucky and southern Ohio has shown that conodonts of the lower part of the Sunbury Shale there represent the Upper *duplicata* Zone, and that the overylying Henly and [lower] Nancy Members of the Borden Formation (Kentucky) or Cuyahoga Formation (Ohio) contain conodonts documenting the lower Osagean Lower *typicus* and Upper *typicus* Zones, respectively (Sandberg and others, 2002; Work and Mason, 2005). Thompson (*in* Work and Mason [2003, p. 593]) reported middle Osagean conodonts from the Nada Member of the Borden Formation in northeastern (Menifee County) Kentucky, and he also (*in* Work and Mason [2004, p. 1128]) reported late Osagean (*texanus* Zone) conodonts from the New Providence Shale Member of the Borden Formation in north-central (Jefferson County) Kentucky.

Leslie and others (1996) reported Kinderhookian faunas from the basal shaly part (Glauconite Shale Bed) of the Fort Payne Formation in southern Kentucky. Their oldest fauna is no older than the *Siphonodella duplicata* Biozone, and they also recovered faunas of the *sandbergi* to Lower *crenulata* zones. The upper part of this thin (28–32 cm thick) shaly unit is Osagean, assignable to a level no older than Middle *anchoralis-latus* Zone, and attesting to the condensed nature of this shaly interval. The overlying carbonate part of the Fort Payne in this area is assignable to the *texanus* Biozone (uppermost Osagean and lowermost Meramecian) (Leslie and others, 1996).

Ruppel (1979), reporting on faunas from the Fort Payne (the carbonate part, exclusive of its basal Maury Shale member) and overlying Tuscumbia formations in northern Alabama, documented the *Gnathodus texanus* Biozones (Osagean) in the Fort Payne and faunas characteristic of the *texanus* to *Synclydagnathus-Cavusgnathus* Biozone (Meramecian) in the Tuscumbia. He correlated the carbonate portion of the Fort Payne, using the conodonts and macrofossils, with the Keokuk Limestone of the Mississippi River Valley succession, and he correlated the Tuscumbia with the Warsaw–Salem–St. Louis formations (uppermost Osagean and Meramecian) in the Mississippi River Valley.

Thompson and others (1971) obtained an Osagean fauna from a limestone at the base of the Rushville Formation of south-central Ohio. They concluded that this fauna was mid-early Osagean, and assignable to the interval now included in the *anchoralis-latus* Zone of Lane and others (1980). The Maxville Limestone that overlies the Rushville contains faunas ranging from upper Meramecian at its base to lower Chesterian in higher levels (Scatterday, 1963).

Chaplin (1979) reported conodonts from Meramecian and Chesterian units in the Hurricane Ridge Syncline of southern West Virginia and adjacent western Virginia. These units include the Little Valley and overlying Hillsdale formations (upper Meramecian), and the lower Chesterian Denmar and “Gasper” formations (of local to regional usage; the stratigraphic nomenclature is complex and often interregionally inconsistent in the eastern Kentucky–southern West Virginia–western Virginia area). Chaplin was able to demonstrate diachroneity of the lower and upper boundaries of both the Little Valley and the Hillsdale in this area using their conodont faunas. The entire succession ranges from the *Taphrognathus-Synclydagnathus* Zone to a level within the *Gnathodus bilineatus–Cavusgnathus* Zone. Stamm (e.g., Stamm, 1997) has collected extensively through the upper Meramecian and Chesterian interval in southeastern West Virginia, and has been able to document additional conodont biozones, using faunas recovered mainly, but not exclusively, from the carbonate units that occur through this interval. Figure 6.2 shows the zones recognized to date. Repetski (unpublished USGS collections) has recovered conodont faunas from the Newman

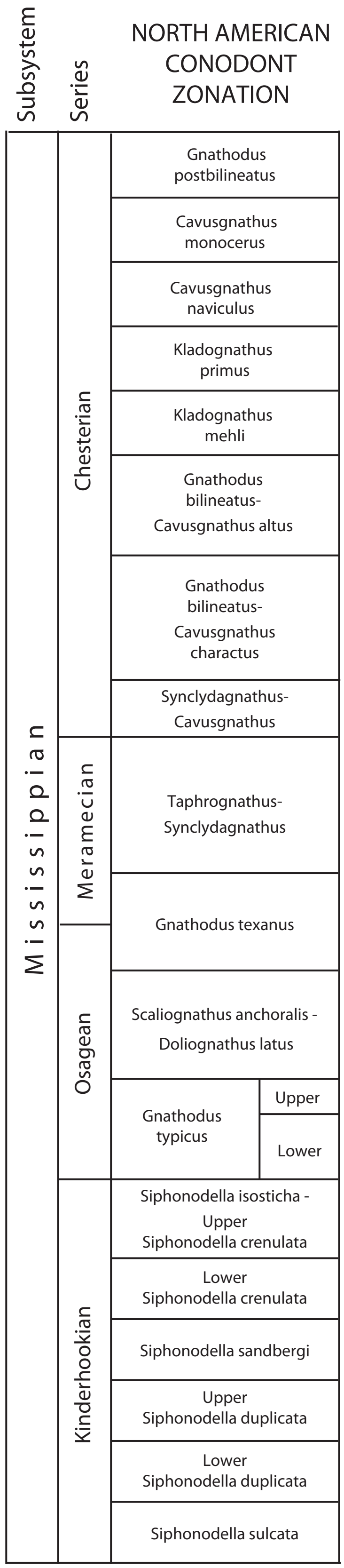

Figure 6.1. Conodont zonation for Mississippian strata in North America. Adapted in part from zonations assembled by Sandberg and others (1978), Lane and others (1980), Collinson and others (1971), and Stamm (1997, and unpublished data).

Limestone at several locations in eastern and northeastern Tennessee. These shallow-water-facies faunas are dominated by long-ranging Meramecian to Chesterian species of *Cavusgnatus, Kladognathus,* and *Hindeodus;* the faunas are mostly low abundance and low diversity. Repetski and Henry (1983) recovered conodonts from the Bramwell Member of the Bluestone Formation of southern West Virginia. The taxa indicate a latest Chesterian age for the unit, and these are the youngest Mississippian conodonts found in the Appalachian Basin. Stamm (1997, and unpublished USGS collections) was able to determine that the Bramwell faunas can be assigned to the latest Chesterian *Gnathodus postbilineatus* Zone.

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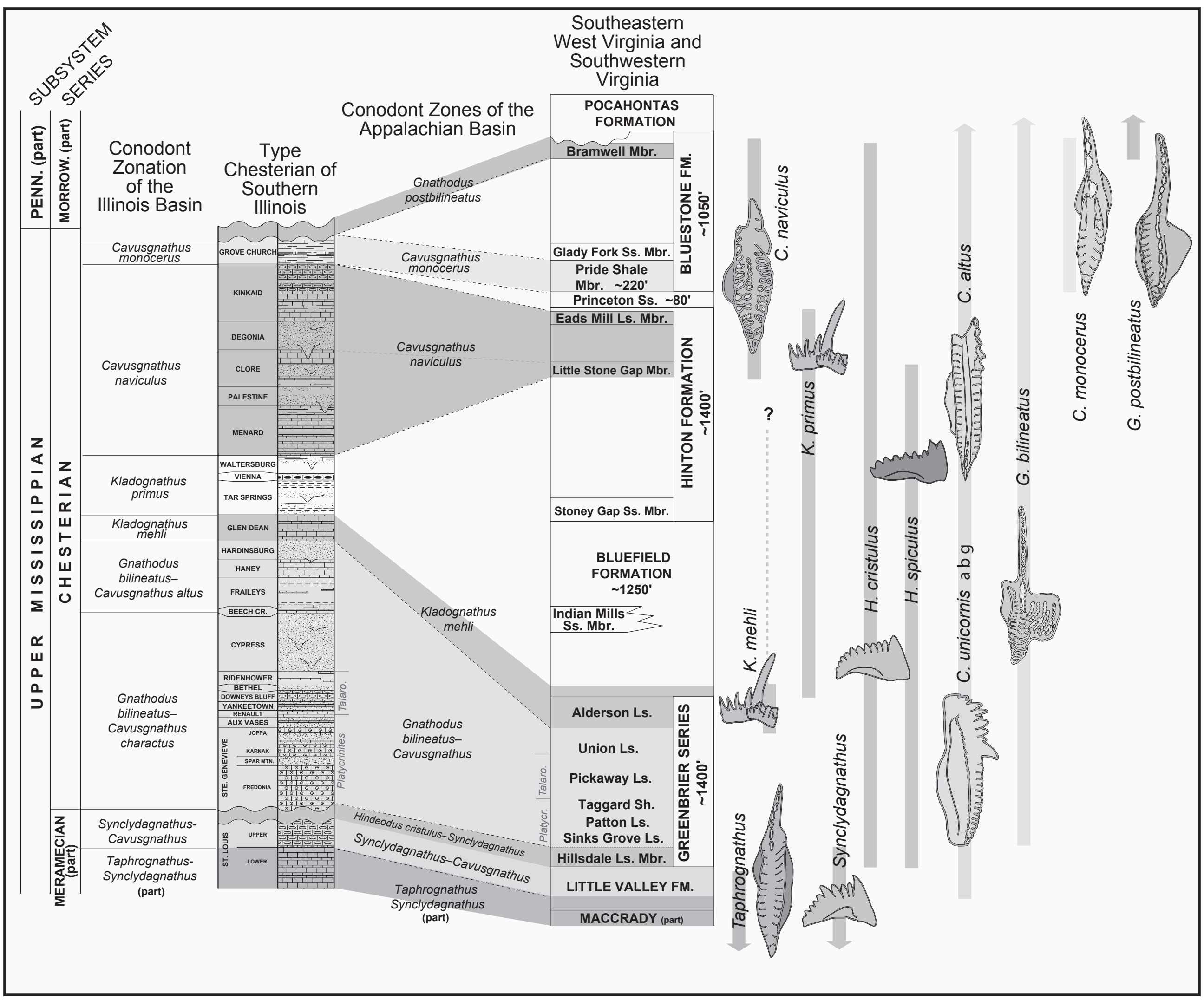

Figure 6.2. Conodont correlation of Upper Mississippian marine strata of the Appalachian Basin (southeastern West Virginia and southwestern Virginia), following Stamm (1997, and unpublished USGS collections), with strata in the Illinois Basin.

7: Mississippian Ammonoids of Alabama

James A. Drahovzal

Mississippian ammonoids occur at several localities in the Interior Low Plateaus and the Valley and Ridge Provinces of Alabama (Fig. 7.1). Although not abundant, the faunas and their localities are of biostratigraphic significance. Two closely associated localities are in Colbert County, Ala., near Braden Point south of Tuscumbia along and near U.S. 43 (Fig. 7.1A). One is in and around a hog lot on the Riner farm east of U.S. 43 (NW ¼, NE ¼, Sec. 12, T 5 S, R 11 W, Tuscumbia quadrangle). The ammonoids are preserved in calcite and limonite in the dark gray shale and light gray lenticular shaly limestone beds of the Pride Mountain Formation (Thomas, 1972), some 50 to 55 ft above the contact with the Tuscumbia Limestone. The fauna here consists of *Lusitanoceras granosum*—formerly *Goniatites granosus*, but reassigned to *Lusitanoceras* by Korn (1988); *Lusitanites subcircularis*—formerly *Neoglyphioceras subcirculare*, but reassigned to *Lusitanites* by Ruzhencev and Bogoslovskaya (1971) (Korn, 1988); *Sulcogirtyoceras limatum*—formerly *Girtyoceras limatum*, but reassigned to *Sulcogirtyoceras* by Ruzhencev and Bogoslovskaya (1971) (Korn, 1988); *Neoglyphioceras utahense*—formerly *Lyrogoniatites newsomi utahensis*, but reassigned to *Neoglyphioceras* by Ruzhencev and Bogoslovskaya (1971) (Korn, 1988); and *Lyrogoniatites* sp. (Furnish and Saunders, 1971; Drahovzal, 1972). The *Lusitanoceras granosum* from this locality constitutes one of the largest of this species found in North America at a diameter of about 52 mm (Drahovzal, 1972). The ammonoids occur with nautiloids and several other invertebrate fossil elements.

The other locality is in the west roadcut and ditch of U.S. 43 (SW ¼, Sec. 12, T 5 S, R 11 W, Tuscumbia quadrangle) just east of Braden Point. Here the goniatites are preserved in limonite in the shales and limestones of the Pride Mountain Formation at a level about 100 to 110 ft above the Tuscumbia Limestone (Fig. 7.1A). Here the fauna consists of *Dombarites choctawensis*—formerly *Goniatites choctawensis*, but reassigned to *Dombarites* by Ruzhencev and Bogoslovskaya (1971); *Sulcogirtyoceras limatum*, and *Neoglyphioceras utahense* (Drahovzal, 1972). Jeff Mayfield of Tuscaloosa, Ala., originally discovered this locality in 1967, and it led to the discovery of the ammonoid fauna found lower in the Pride Mountain Shale nearby.

Another ammonoid fauna occurs in two closely associated localities in the Valley and Ridge Province north of Trussville, Jefferson County, Ala (Fig. 7.1B). One locality is at the northeastern end of the abandoned Vann's Quarry (SE ¼, NE ¼, NE ¼, Sec. 14, T16 S, R 1W, Argo quadrangle) (Butts, 1926, Plate 50b). Here the contact of the Tuscumbia Limestone and the Pride Mountain Formation dips about 7° southeast (Kidd and Shannon, 1977, p. 17). The ammonoids are preserved in pyrite, limonite, and siderite, and are commonly associated with siderite nodules in the dark gray to black fissile shale of the Pride Mountain Formation. *Lyrogoniatites georgiensis* and *Girtyoceras meslerianum* occur in the basal 2 to 3 ft and *Lyrogoniatites georgiensis* occurs throughout, up to about 20 ft above the contact with the Tuscumbia Limestone. Just south of the quarry (NW ¼, SE ¼, Sec.14, T16 S, R1W) the yards of private homes at the time they were being built (in the late 1960's) contained *Lyrogoniatites georgiensis* associated with siderite nodules of the Pride Mountain Formation.

Scattered Mississippian ammonoids are known and have been collected from the Pride Mountain Formation and Floyd Shale at other localities in Alabama. They include the ditch along Ala. 247 near Fielder Ridge, Colbert County; a roadcut on U.S. 31 north of Hartselle, Morgan County; near the Hercules Powder Plant at Bessemer; Greenwood Sink near Greenwood, and drillholes near Five Points East in Irondale, Jefferson County; on the eastern flank of Oak Mountain near Pelham, Shelby County; in a railroad cut east of Odenville and a low roadcut at the northern edge of Pell City, St. Clair County; and near Blount Springs and in the vicinity of Sky Ball, Blount County. All Alabama specimens currently reside in the paleontological collections at the Kentucky Geological Survey in Lexington, Ky.

The fauna from the two locations in Colbert County, Ala., discussed in detail above, contains elements that are very similar to those found in the Ruddell Member of the Moorefield Formation near Batesville, Ark. (Drahovzal, 1966, 1972; Saunders and others, 1977) and to faunas known from the Slade Formation in Rowan County, Ky. (Work and Mason, *this volume*) and from an unknown horizon in Rockcastle County, Ky. (Miller, 1889; Miller and Furnish, 1940; Furnish and Saunders, 1971). These areas are in the Interior Low Plateaus and the Ozark Plateaus Provinces. The fauna found in Jefferson County, Ala., is apparently of a similar age as that of Colbert County, Ala., but contains both *Lyrogoniatites georgiensis* and *Girtyoceras meslerianum*, the same two genera as described from the Floyd Shale, north of Rome, Floyd County, Ga. (Miller and Furnish, 1940; Allen and Lester, 1954). Both of the latter localities are in the Valley and Ridge Province, suggesting that there may have been paleoenvironmental, paleogeographic, or both types of controls acting on the distribution of ammonoid species during the deposition of the Pride Mountain Formation, the Floyd Shale, and their equivalents in the central and eastern United States.

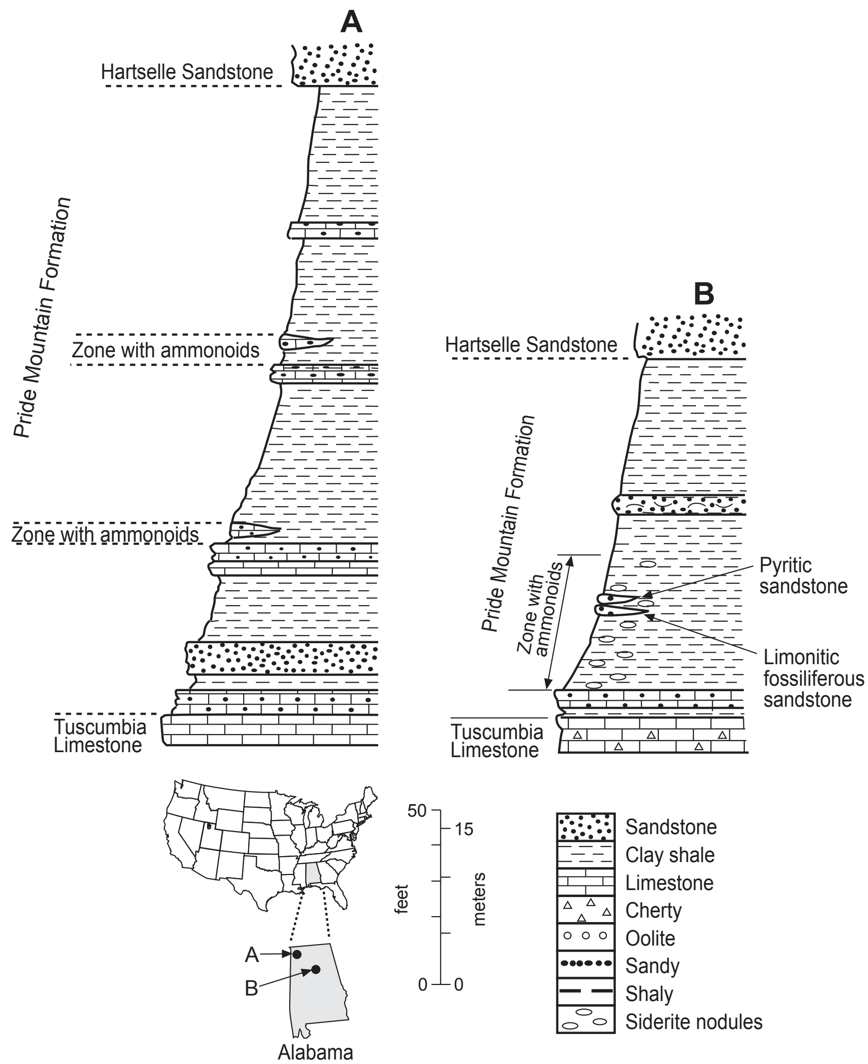

Figure 7.1. Location and measured sections of sampling localities in the Tuscumbia quadrangle, Colbert County, Alabama.

Acknowledgments

This manuscript is dedicated to the memory of a mentor and friend, William M. Furnish (1912–2007). I would like to thank David Work and Dieter Korn for their advice in updating the systematic nomenclature and in supplying me with some of the more recent references. I also would like to thank Charles Mason for making several useful suggestions after reading the original text. Donald Chesnut suggested that I contribute the paper to this volume and Cortland Eble and Meg Smath edited the text. Collie Rulo drafted the illustrations. I am indebted to them all.

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8: The Mississippian Ammonoid Succession in the Central Appalachian Basin, Eastern Kentucky

David M. Work and Charles E. Mason

Introduction

The central Appalachian Basin contains a significant Lower–Upper Mississippian (Kinderhookian-Chesterian) ammonoid sequence. This succession includes ammonoids diagnostic of the middle and upper Tournaisian (*Goniocyclus-Protocanites*, *Pericyclus-Muensteroceras*, and *Fascipericyclus-Ammonellipsites* Zones) and the upper Viséan (*Lusitanoceras-Lyrogoniatites* Zone). Although no comprehensive systematic description of these ammonoids has been published, Gordon and Mason (1985) presented summaries of faunal and biostratigraphic relationships for the Osagean (upper Tournaisian–Viséan) sequence in the Borden Formation in eastern and north-central Kentucky, elements of which have recently been described by Work and Manger (2002) and Work and Mason (2003, 2004, 2005). Continued collecting in eastern Kentucky has yielded at least 5,000 ammonoids comprising 18 genera and representing at least five major ammonoid intervals. Altogether, four ammonoid assemblages comprising two to five genera (12 genera total) are recognized within the Kinderhookian-Osagean part of the sequence, with two assemblages comprising two to four genera (six genera total) in the Chesterian (Fig. 8.1). In the following discussion, the Mississippian ammonoid assemblages are treated individually, in ascending order, beginning with the Henley Bed (Plate 8.1).

Ammonoid Biostratigraphy

Late Kinderhookian

The oldest Mississippian ammonoid assemblage in the Appalachian Basin occurs above the base of the Henley Bed of the Borden Formation in northeastern Kentucky and the equivalent Henley Member of the Cuyahoga Formation in south-central Ohio. Conodonts from the Henley indicate a late Kinderhookian to early Osagean (middle to early late Tournaisian) age, beginning in the Lower *Siphonodella crenulata* Zone and extending into the Upper *Gnathodus typicus* Zone (Sandberg and others, 2002). An assemblage of largely immature goniatites, including *Gattendorfia* n.sp. and *Imitoceras?* sp., has been recovered from the basal 10 cm of the Henley (Jacobs Chapel Shale equivalent), associated with conodont faunas indicative of the Lower *Siphonodella crenulata* Zone, as determined by C.A. Sandberg (U.S. Geological Survey, personal communication, 2001; Sandberg and others, 2002). Both ammonoids and conodonts indicate an early late Kinderhookian (middle Tournaisian, middle Hastarian Substage) age, corresponding to the lower part of the *Goniocyclus-Protocanites* Zone of Kullman and others (1991).

Early Osagean

Ammonoids from the lower part of the Borden Formation in northeastern Kentucky (Mason and Chaplin, 1979; Gordon and Mason, 1985, p. 193, sections B and C in Fig. 2; Work and Manger, 2002; Work and Mason, 2005), which include *Muensteroceras oweni* (Hall) (Plate 8.1: Figs. 11–13), *M. parallelum* (Hall), *Kazakhstania mangeri* Work and Mason (Plate 8.1: Figs. 9–10), *Imitoceras ixion* (Hall), *Masonoceras kentuckiense* Work and Manger (Plate 8.1: Figs. 3–5), and *Protocanites lyoni* (Meek and Worthen), are associated with conodonts, including *Polygnathus communis carina* Hass, *Pseudopolygnathus multistriatus* Mehl and Thomas, *Gnathodus typicus* Cooper, and *G. semiglaber* Bischoff, of early Osagean (Fern Glen or early Burlington) age, as determined by C.A. Sandberg (cited in Work and Manger [2002] and Work and Mason [2005]). This interval, which ranges from the top of the Farmers Member into strata referable to the Cowbell Member (Fig. 8.1), was placed in the *Muensteroceras oweni* Assemblage Zone by Gordon and Mason (1985) and Work and Mason (2005) and indicates correlation to the lower Ivorian Substage (*Pericyclus-Muensteroceras* Zone) of the Belgian upper Tournaisian succession. *Muensteroceras oweni* zonal faunas, which include elements common or similar to the Borden assemblage, are also known from the base of the New Providence Formation (Rockford Limestone) in southern Indiana (Lineback, 1963; Manger, 1979; Gordon and Mason, 1985; Gordon, 1986), the upper part of the Cuyahoga Formation and the lower part of the Logan Formation in southern and central Ohio (Hyde, 1953; Manger, 1971; Gordon and Mason, 1985), and the lower part of the Marshall Sandstone in eastern Michigan (Miller and Garner, 1955); see Gordon and Mason (1985) for discussion and references.

Middle Osagean

The succeeding middle Osagean (middle Burlington) interval in the middle part of the Borden Formation includes *Dzhaprakoceras* n.sp. (*Bollandites* n.sp. and *Bollandites?* sp. of Gordon and Mason [1985, p. 193–194, sections B and C in Fig. 2]) from the middle and upper part of the Cowbell Member near Morehead, Rowan County, Ky.; *Dzhaprakoceras* n.sp. and *Merocanites* sp. from the middle of the Cowbell Member at Stanton, Powell County, Ky. (Gordon and Mason, 1985, p. 194, section E in Fig. 2); and *Eurites* n.sp. and *Merocanites drostei* Collinson from the upper part of the Nancy Member near Berea, Madison County, Ky. (Gordon and Mason, 1985, p. 193, section F in Fig. 2). The upper and lower limits of this interval are poorly constrained, but it

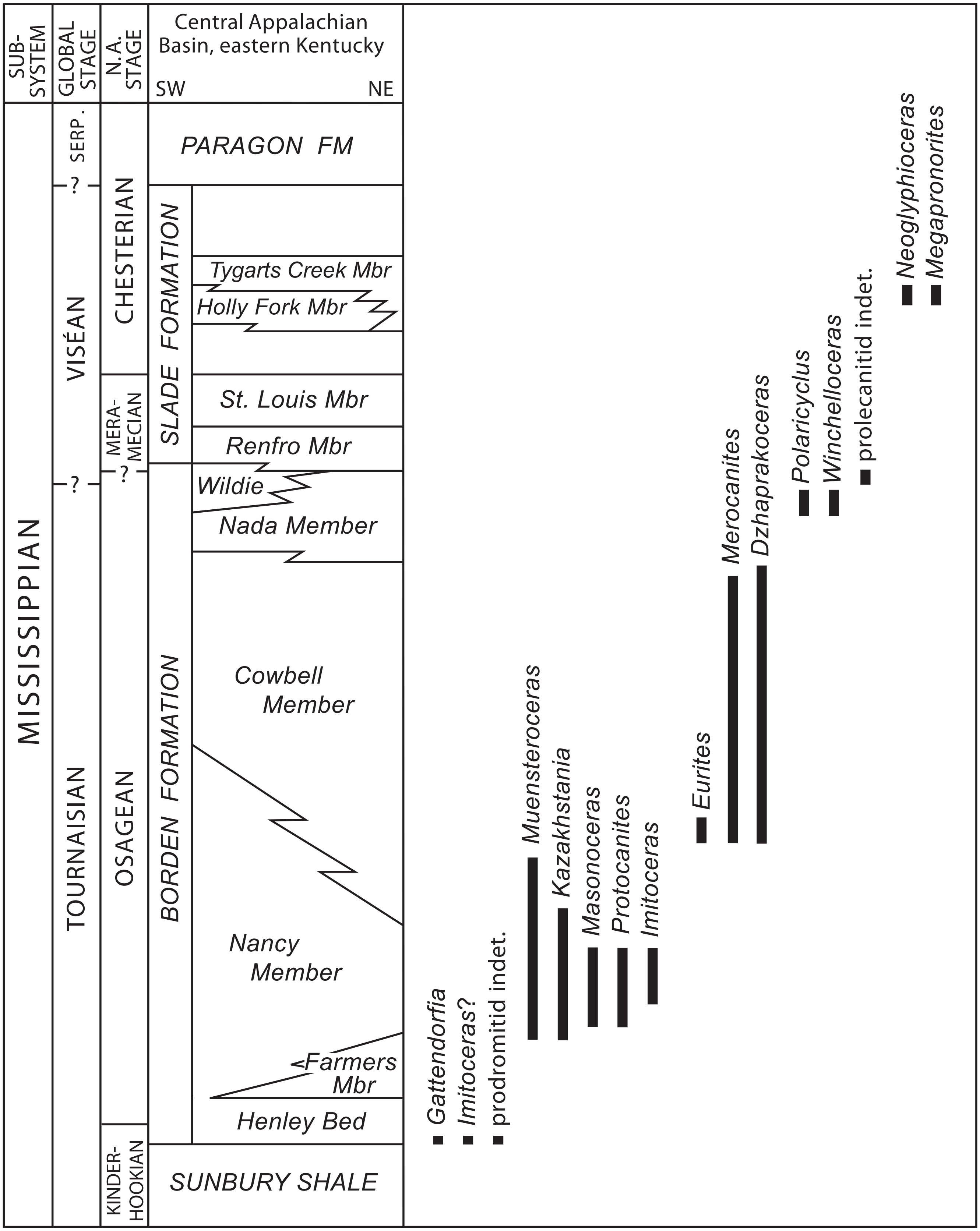

Figure 8.1. Stratigraphic distribution of Mississippian ammonoid genera in the central Appalachian Basin, eastern Kentucky.

appears to be equivalent to parts of the upper Courceyan or lower Chadian Substages (lower *Fascipericyclus-Ammonellipsites* Zone) in the British upper Tournaisian succession (*sensu* Riley, 1991, 1993, 1996).

A higher middle Osagean ammonoid assemblage characterized by *Polaricyclus bordenensis* Work and Mason (Plate 8.1: Figs. 6–8) and *Winchelloceras allei* (Winchell) (includes *Eogonioloboceras?* sp. of Gordon and Mason [1985, p. 194]) occurs near the top of the Borden Formation in the upper part of the Nada Member near Frenchburg, Menifee County, Ky. (Gordon and Mason, 1985, p. 194, section D in Fig. 2; Work and Mason, 2003). Conodonts associated with *Polaricyclus* and *Winchelloceras* at the Frenchburg locality, including *Gnathodus bulbosus* Thompson, indicate a late middle Osagean (latest Burlington) age (T.L. Thompson, cited in Work and Mason [2003]), and thus support reference of the Nada assemblage to a relatively high (middle Chadian, uppermost Tournaisian) level in the *Fascipericyclus-Ammonellipsites* Zone.

Middle Chesterian

Two Chesterian *Lusitanoceras-Lyrogoniatites* Zone ammonoid assemblages are recognized in the Slade Formation in northeastern and south-central Kentucky. A middle Chesterian assemblage consisting almost entirely of *Neoglyphioceras hartmani* (Furnish and Saunders) occurs in the upper part of the Holly Fork Member and lower part of the Tygarts Creek Member of the Slade Formation in sections near Morehead, Rowan County, Ky. The presence of *Neoglyphioceras hartmani* in the Holly Fork–Tygarts Creek assemblage indicates correlation to the Beech Creek Limestone in the type Chesterian succession in southwestern Illinois. This interval was referred to the *Lusitanoceras granosum* Zone (P_2) by Saunders and others (1977) and correlates with the middle or upper Brigantian Substage of the British upper Viséan succession. The well-known *Lusitanites subcircularis* fauna from near Crab Orchard, in Rockcastle County, south-central Kentucky (Miller and Furnish, 1940; see Furnish and Saunders [1971] for discussion) is broadly comparable in age to the Holly Fork–Tygarts Creek assemblage. It includes *Lusitanites subcircularis* (Miller) (Plate 8.1: Figs. 1–2), *Sulcogirtyoceras limatum* (Miller and Faber) (Plate 8.1: Figs. 14, 17), *Dombarites choctawensis* (Shumard) (Plate 8.1: Figs. 15–16), and *Metadimorphoceras edwini* (Miller and Furnish), which, according to Furnish and Saunders (1971), occur in strata referable to the Newman Limestone (Slade Formation of Ettensohn and others [1984]). This assemblage represents a well-established biostratigraphic datum and indicates correlation to the upper Brigantian Substage (*Lusitanites subcircularis* Zone, P_2b) of the British upper Viséan succession (Saunders and others, 1977; Riley, 1993). Comparable assemblages are also known from the lower Caney Formation (Delaware Creek Member) in Oklahoma, the upper Moorefield Formation in Arkansas (Furnish and Saunders, 1971; Drahovzal, 1972; Saunders and others, 1977), and the lower Pride Mountain Formation in Alabama (Drahovzal, 1972).

Conclusions

The Mississippian of the central Appalachian Basin in eastern Kentucky contains an intermittent succession of five major ammonoid intervals. The Kinderhookian sequence (middle Tournaisian) in the basal Borden Formation has yielded one ammonoid assemblage, which characterizes the lower 10 cm of the Henley Bed (*Gattendorfia-Imitoceras?)*. The Osagean sequence (early late to latest Tournaisian) in the Borden Formation contains three major ammonoid assemblages, which characterize the uppermost Farmers, Nancy, and basal Cowbell Members (*Muensteroceras-Kazakhstania*), the middle to upper Cowbell Member (*Dzhaprakoceras-Merocanites*), and the Nada Member (*Polaricyclus-Winchelloceras*). The Chesterian sequence (late Viséan) in the Slade Formation has yielded two ammonoid assemblages, which characterize the Holly Fork and Tygarts Creek Members (*Neoglyphioceras*) and an undetermined level in the Slade-equivalent Newman Limestone (*Lusitanites-Sulcogirtyoceras*). Early Kinderhookian, latest Kinderhookian, Meramecian–early Chesterian, and late Chesterian ammonoids are presently unknown from the central Appalachian Basin.

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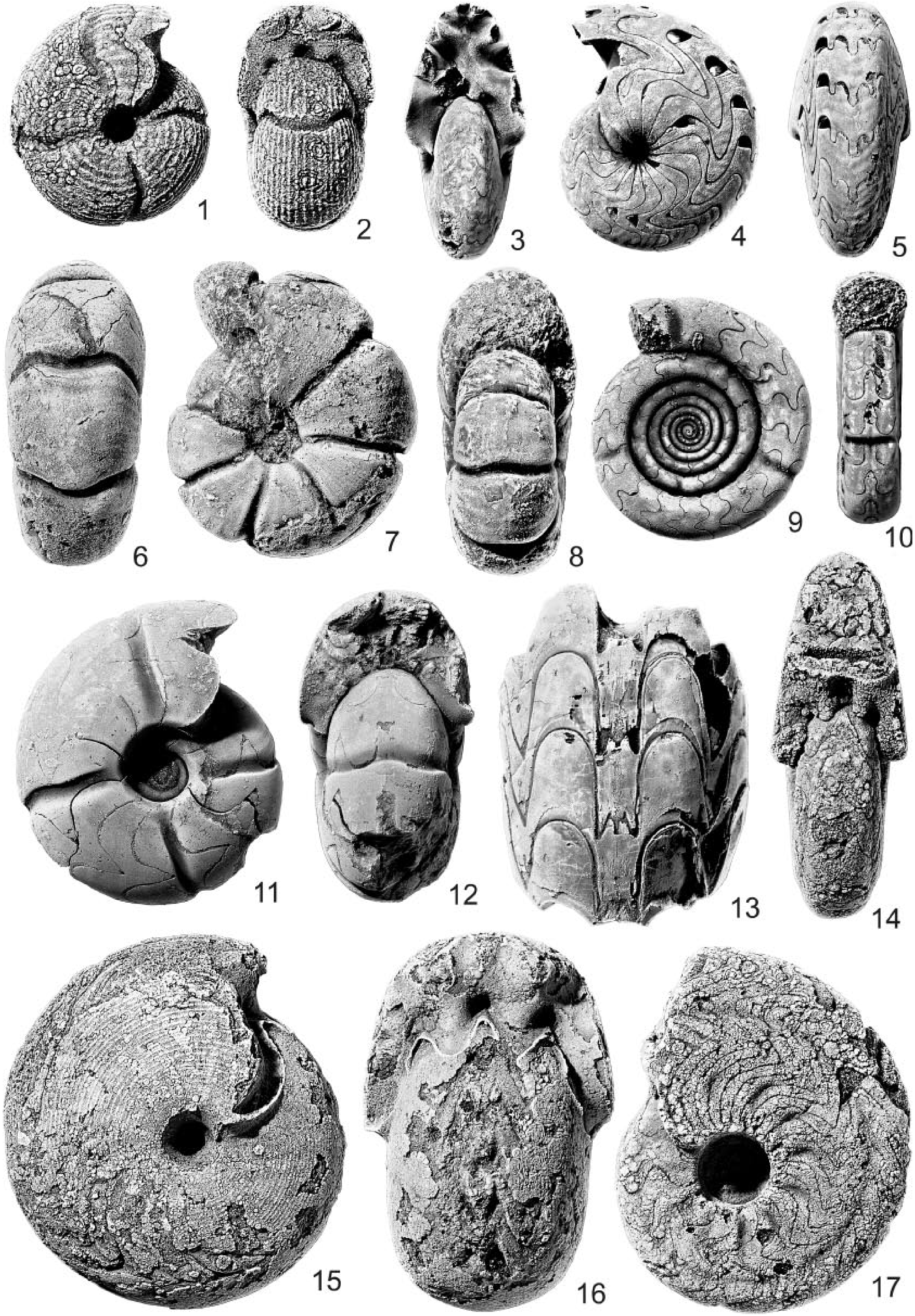
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Plate 8.1. Mississippian ammonoids from the central Appalachian Basin. Figured specimens are reposited at the Department of Geology, University of Iowa, Iowa City, Iowa (SUI), and the Field Museum of Natural History, Chicago (WMUC). 1, 2. *Lusitanites subcircularis* (Miller, 1889). Topotype SUI 34397, X4, Slade Formation, middle Chesterian, near Crab Orchard, in Rockcastle County, south-central Kentucky. 3–5. *Masonoceras kentuckiense* Work and Manger, 2002. Paratype SUI 95341, X3.5, Nancy Member, Borden Formation, lower Osagean, near Morehead, Rowan County, northeastern Kentucky. 6–8. *Polaricyclus bordenensis* Work and Mason, 2003. Holotype SUI 95344, X3.5, Nada Member, Borden Formation, middle Osagean, near Frenchburg, Menifee County, northeastern Kentucky. 9, 10. *Kazakhstania mangeri* Work and Mason, 2005. Paratype SUI 98103, X3.5, Nancy Member, Borden Formation, lower Osagean, near Morehead, Rowan County, northeastern Kentucky. 11–13. *Muensteroceras oweni* (Hall, 1860). Hypotype SUI 98115, X3.5, Nancy Member, Borden Formation, lower Osagean, near Morehead, Rowan County, northeastern Kentucky. 14, 17. *Sulcogirtyoceras limatum* (Miller and Faber, 1892). Holotype WMUC 8753, X3.5, Slade Formation, middle Chesterian, near Crab Orchard, in Rockcastle County, south-central Kentucky. 15, 16. *Dombarites choctawensis* (Shumard, 1863). Hypotype WMUC 6211, X1.2, Slade Formation, middle Chesterian, near Crab Orchard, in Rockcastle County, south-central Kentucky.

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9: The Pennsylvanian Ammonoid Succession In the Appalachian Basin

David M. Work, Charles E. Mason, and Royal H. Mapes

Introduction

The Pennsylvanian succession in the Appalachian Basin contains an intermittent record of stratigraphically isolated Atokan-Virgilian ammonoid assemblages. Elements of these assemblages have been described in taxonomic papers by Miller and Unklesbay (1942, 1947), Miller and Sturgeon (1946), Sturgeon and Miller (1948), Furnish and Knapp (1966), Eagar (1970), Saunders (1971), Boardman and others (1994), and Mapes and others (1997). The Pennsylvanian ammonoid biostratigraphy, principally from the northern sequence in eastern Ohio and western Pennsylvania, was summarized by Boardman and others (1994) and Mapes and others (1997). Rice and others (1994a) and Chesnut (1991) summarized the Morrowan-Atokan boundary interval in the southern sequence in eastern Kentucky. These data are summarized with taxonomic revision in Figures 9.1 and 9.2. Although the coverage attempts to be comprehensive, this review is restricted to treatment of faunal studies that are accompanied by photographic illustrations or of material available to us. In the following discussion, the Pennsylvanian ammonoid assemblages are treated individually, in ascending order, beginning with the Betsie Shale Member (Plate 9.1).

Ammonoid Biostratigraphy

Late Morrowan or Early Atokan

The oldest Pennsylvanian ammonoid assemblage in the central Appalachian Basin occurs in the Betsie Shale Member of the Pikeville Formation in eastern Kentucky (Eagar, 1970). This fauna has not yet been well studied, but contains *Gastrioceras* sp. (*G.* aff. *subcrenatum* of Eagar [1970]) and *Wiedeyoceras?* sp. (*Anthracoceras arcuatilobum* Group of Eagar [1970]). Elsewhere, the Betsie Shale contains *Linoproductus nodosus* Zone brachiopods, which indicate a late Morrowan or early Atokan age for this unit, equivalent to the upper part of the Bloyd Formation (Dye Shale or Kessler Limestone Members) or the lower part of the Atoka Formation (Trace Creek Shale Member) in the type Morrowan succession (Henry and Sutherland, 1977; Sutherland and Henry, 1980).

Early Atokan

An early Atokan ammonoid assemblage characterized by *Diaboloceras neumeieri* Quinn and Carr (Plate 9.1: Figs. 9–10) in association with *Dimorphoceratoides campbellae* Furnish and Knapp (Plate 9.1: Fig. 15) and *Gastrioceras occidentale* (Miller and Faber) occurs in the Kendrick Shale Member of the Hyden Formation in eastern Kentucky (Furnish and Knapp, 1966). The Kendrick interval was referred to the *Diaboloceras neumeieri* Zone by Saunders and others (1977), equivalent to a position just below the top of the Trace Creek Shale Member of the Atoka Formation in the type Morrowan succession and near the Westphalian B-C boundary in western Europe (Rice and others, 1994a). Comparable assemblages, which include the Kendrick form *Dimorphoceratoides campbellae* together with *Phaneroceras* and *Gastrioceras,* are also known from the Lowellville (Poverty Run) limestone unit of the Pottsville Group in northeastern Ohio (Mapes and others, 1997).

A slightly higher Atokan assemblage from the Magoffin Member of the Four Corners Formation in eastern Kentucky includes *Phaneroceras compressum* (Hyatt) (Plate 9.1: Figs. 13–14), *Gastrioceras* cf. *G. occidentale* (Plate 9.1: Figs. 11–12), and possibly *Neoicoceras elkhornense* (Miller and Gurley), correlating with the post–Trace Creek sequence in the Atoka Formation of the Ozark Shelf and to the upper part of the Westphalian B in western Europe (Rice and others, 1994a).

Middle or Late Atokan

Higher Atokan assemblages with *Paralegoceras* and *Gastrioceras* occur in the Lower Mercer limestone unit of the Pottsville Group in central Ohio (Mapes and others, 1997), indicating a probable *Paralegoceras texanus* Zone equivalent. Elsewhere, the Lower Mercer contains middle Atokan fusulinid assemblages characterized by *Fusulinella iowensis* Thompson, making this unit younger than the Kendrick or Magoffin Members in Kentucky (Douglas, 1987; Rice and others, 1994b, p. 19).

Early Desmoinesian

A succession of three *Wellerites* Zone ammonoid assemblages is recognized in the Allegheny Group in east-central and northeastern Ohio. *Wellerites mohri* Plummer and Scott and *Aktubites trifidus* Ruzhencev (Plate 9.1: Figs. 7–8) occur with *Gastrioceras* s.l. in the Putnam Hill limestone unit of the Allegheny Group in northeastern Ohio (Miller and Sturgeon, 1946; Mapes and others, 1997). This interval was referred to the lower part of the *Wellerites* Zone (*Paralegoceras* Subzone) by Boardman and others (1994) and indicates correlation to the early Desmoinesian lower Cherokee Group (lower Boggy Formation) in the Midcontinent Middle Pennsylvanian succession.

Middle Desmoinesian

The succeeding middle Desmoinesian interval in the middle part of the Allegheny Group includes *Wellerites mohri* (Plate 9.1: Figs. 5–6), *Gonioglyphioceras columbianense* Mapes, Windle, Sturgeon, and Hoare, and

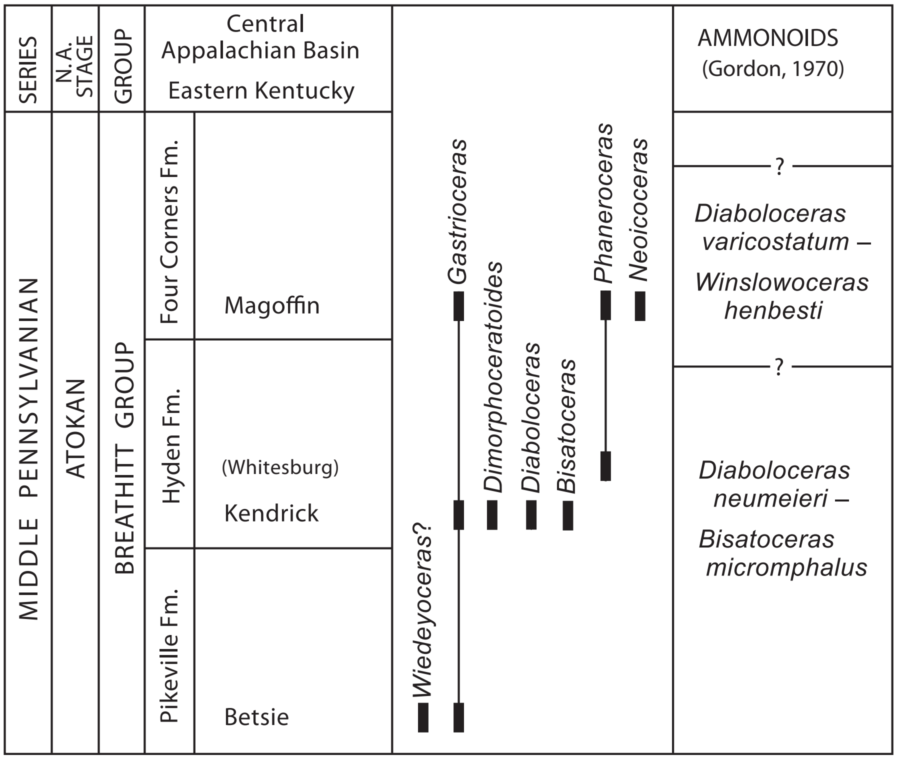

Figure 9.1. Distribution of Pennsylvanian (Atokan) ammonoid genera in the south-central Appalachian Basin, eastern Kentucky.

Somoholites sagittarius Saunders from the Columbiana unit in eastern Ohio (Mapes and others, 1997). Precise correlation of this interval is uncertain at present, but it indicates a middle Desmoinesian age corresponding to the middle part of the *Wellerites* Zone (*Politoceras* Subzone) in the Midcontinent Middle Pennsylvanian succession.

Late Desmoinesian

A third, slightly higher Desmoinesian ammonoid assemblage from the Washingtonville shale unit of the Allegheny Group in northeastern Ohio includes *Wellerites mohri, Gonioglyphioceras gracile* (Girty), and *Somoholites saundersi* Mapes, Windle, Sturgeon, and Hoare, in addition to *Maximites* and *Glaphyrites* (Mapes and others, 1997). The co-occurrence of *Wellerites mohri* and *Gonioglyphioceras gracile* in the Washingtonville indicates an early late Desmoinesian age for this unit, equating to the upper Fort Scott cyclothem (Little Osage and equivalent Wetumka Shales) in central Oklahoma.

Early Missourian

Ammonoids from the lower part of the Conemaugh Group in eastern Ohio (Sturgeon and Miller, 1948; Mapes and others, 1997) and western Pennsylvania (Miller and Unklesbay, 1942, 1947) that include *Pennoceras seamani* Miller and Unklesbay (Plate 9.1: Figs. 1–2), *Schistoceras missouriense* (Miller and Faber) (Plate 9.1: Figs. 3–4), and representatives of *Neoaganides* and *Gonioloboceras* are associated with conodonts of late early Missourian age, as determined by Heckel and Barrick (Heckel, 1999, p. 94). This interval, which includes the lower Brush Creek limestone and upper Brush Creek limestone (Pine Creek) units, was referred to the *Pennoceras* Zone (Upper Subzone) by Boardman and others (1994) and indicates correlation to the early Missourian Swope (Hushpuckney Shale) and Dennis (Stark Shale) cyclothems in the Midcontinent Upper Pennsylvanian succession.

Middle Missourian

Higher Missourian ammonoid assemblages recorded from the Conemaugh Group include *Preshumardites gaptankensis* (Miller) from the Carnahan Run (Woods Run) marine unit (Saunders, 1971) in western Pennsylvania and *Neoaganides*, *Subkargalites*, and *Gonioloboceras* from the equivalent Portersville shale unit in northeastern Ohio (Mapes and others, 1997). This interval was referred to the *Preshumardites* Zone (*Preshumardites gaptankensis* Subzone) by Boardman and others (1994) and indicates correlation to the middle Missourian Iola cyclothem (Muncie Creek Shale) in the Midcontinent Upper Pennsylvanian succession.

Early Virgilian

Schistoceras has been reported from the upper part of the Conemaugh Group (Ames limestone unit) in eastern Ohio (Mapes and others, 1997) and southwestern Pennsylvania (Miller and Unklesbay, 1942), indicating a probable *Shumardites* Zone equivalent. Elsewhere, the Ames contains *Idiognathodus simulator* Zone conodonts, which indicate an early, but not earliest, Virgilian (earliest Gzhelian) age for this unit, equating to the Oread cyclothem (Heebner Shale) in the northern Midcontinent (Barrick and others, 2004; Heckel and others, 2007; P.H. Heckel, University of Iowa, personal communication, 2007).

Conclusions

Middle and Upper Pennsylvanian strata in the Appalachian Basin contain an intermittent succession of 12 stratigraphically isolated ammonoid assemblages. The Atokan sequence in the Breathitt and Pottsville Groups contains four major ammonoid assemblages, which characterize the Betsie Shale Member of the Pikeville Formation *(Gastrioceras),* the Kendrick Shale Member of the Hyden Formation *(Diaboloceras-Dimorphoceratoides),* the Magoffin Member of the Four Corners Formation

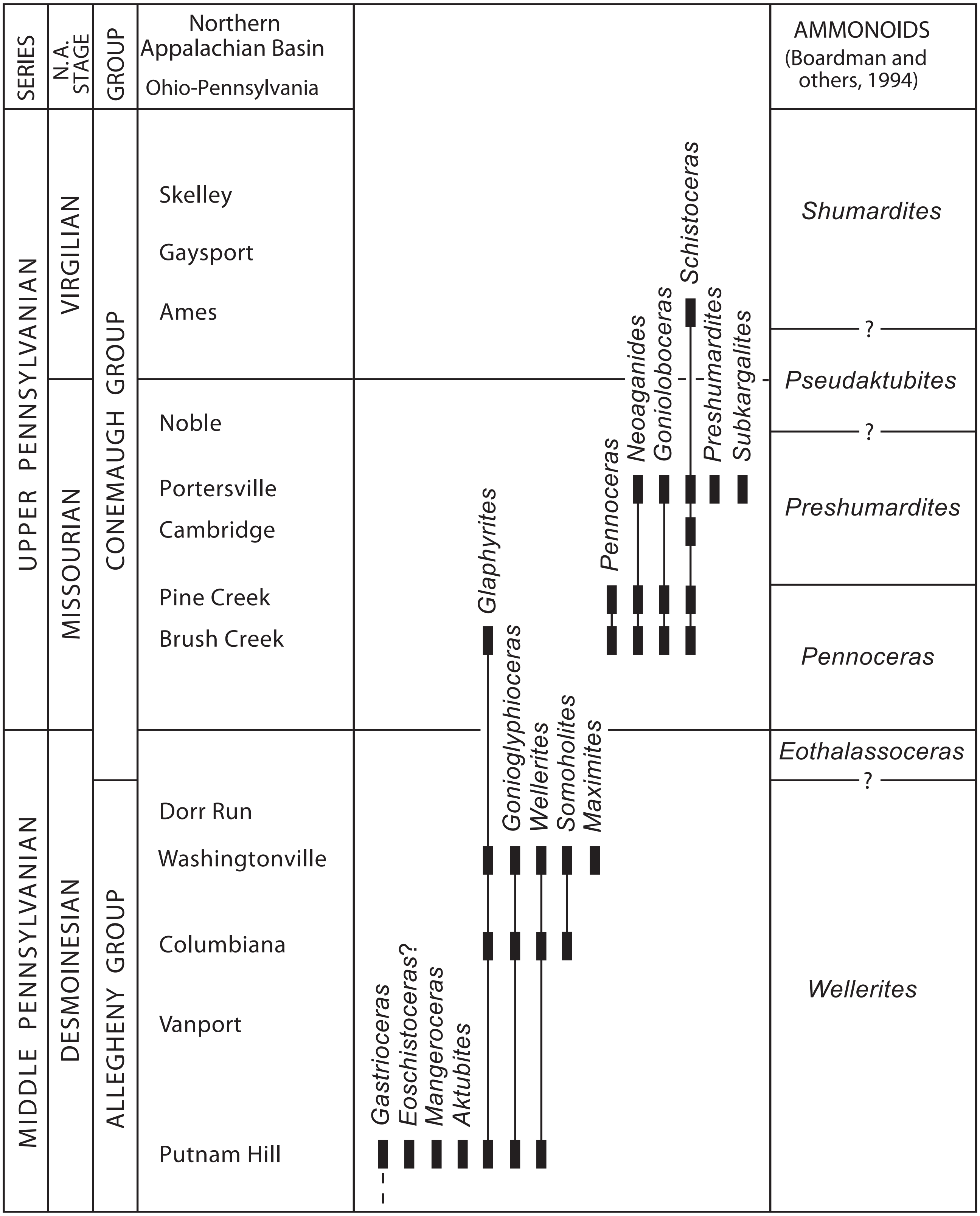

Figure 9.2. Distribution of Pennsylvanian (Desmoinesian-Virgilian) ammonoid genera in the north-central part of the Appalachian Basin, Ohio and Pennsylvania.

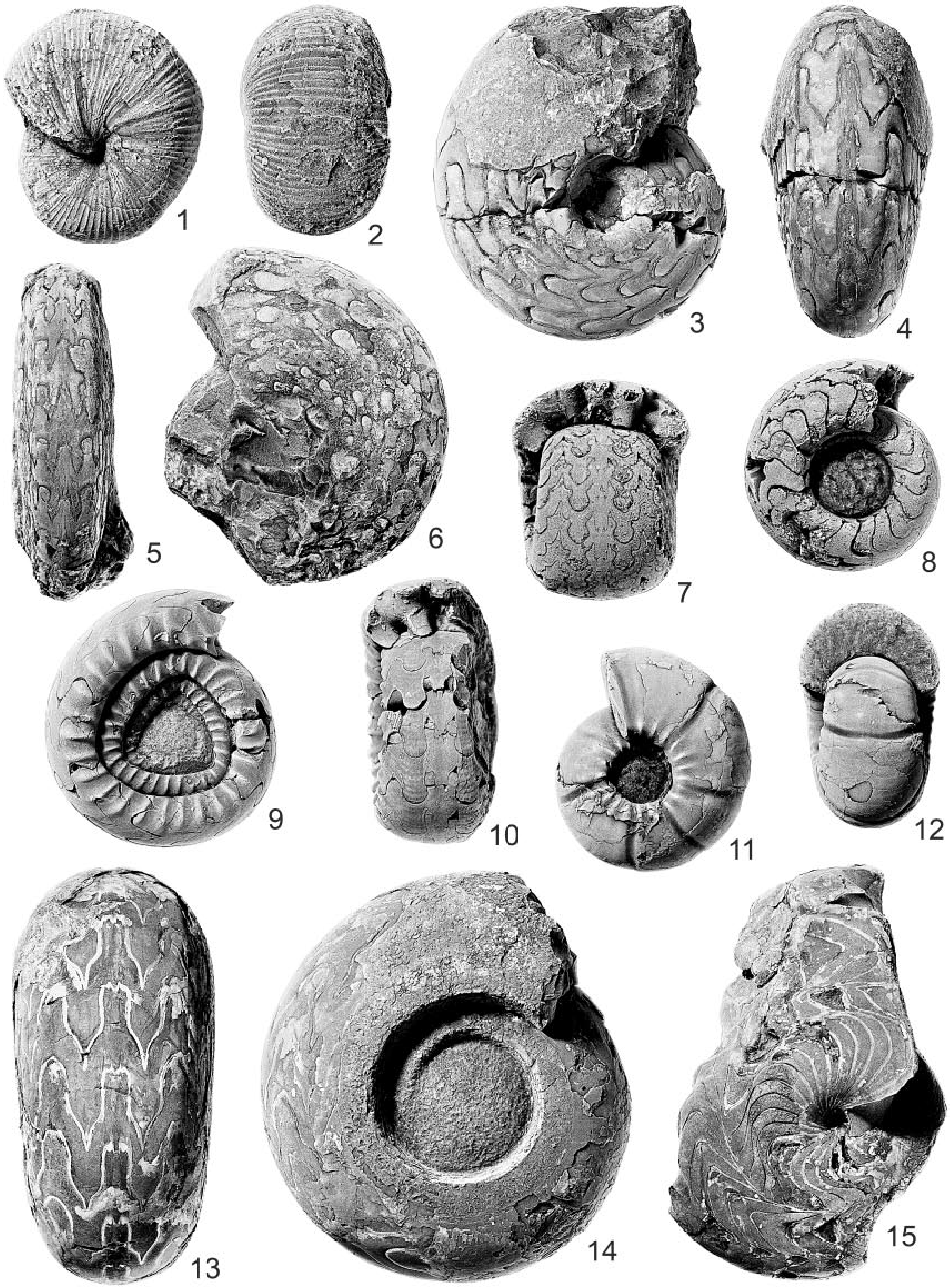
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Plate 9.1. Pennsylvanian ammonoids from the Appalachian Basin. Figured specimens are reposited at the Department of Geology, University of Iowa, Iowa City, Iowa (SUI), the Orton Geological Museum, Department of Geological Sciences, Ohio State University, Columbus, Ohio (OSU), and the Carnegie Museum of Natural History, Pittsburgh, Pa. (CM). 1, 2. *Pennoceras seamani* Miller and Unklesbay, 1942. Syntype CM 22293, X2.5, lower Brush Creek limestone, Conemaugh Group, lower Missourian, near Witmer, Allegheny County, southwestern Pennsylvania. 3, 4. *Schistoceras missouriense* (Miller and Faber, 1892). Hypotype SUI 1437, X1.25, Cambridge limestone, Conemaugh Group, middle Missourian, near New Concord, Guernsey County, eastern Ohio. 5, 6. *Wellerites mohri* Plummer and Scott, 1937. Hypotype OSU 30726, X 1.25, Columbiana unit, Allegheny Group, middle Desmoinesian, near Franklin Square, Columbiana County, eastern Ohio. 7, 8. *Aktubites trifidus* Ruzhencev, 1955. Hypotype OSU 30723, X4, Putnam Hill limestone, Allegheny Group, lower Desmoinesian, near Canfield, Mahoning County, eastern Ohio. 9, 10. *Diaboloceras neumeieri* Quinn and Carr, 1963. Hypotype SUI 11852, X1.5, Kendrick Shale Member, Hyden Formation, Breathitt Group, lower Atokan, Cow Creek, Floyd County, eastern Kentucky. 11, 12. *Gastrioceras* cf. *G. occidentale* (Miller and Faber, 1892). SUI 104276, X2, Magoffin Member, Four Corners Formation, Breathitt Group, Atokan, near Prestonsburg, Floyd County, eastern Kentucky. 13, 14. *Phaneroceras compressum* (Hyatt, 1891). SUI 104277, X1.2, Magoffin Member, Four Corners Formation, Breathitt Group, Atokan, near Prestonsburg, Floyd County, eastern Kentucky. 15. *Dimorphoceratoides campbellae* Furnish and Knapp, 1966. Holotype SUI 11854, X1.5, Kendrick Shale Member, Hyden Formation, Breathitt Group, lower Atokan, Cow Creek, Floyd County, eastern Kentucky.

(Phaneroceras), and the Lower Mercer limestone unit of the Pottsville Group *(Paralegoceras)*. The Desmoinesian sequence in the Allegheny Group contains three major ammonoid assemblages, which characterize the Putnam Hill limestone unit *(Wellerites-Aktubites)* and the Columbiana unit and Washingtonville shale unit *(Wellerites-Gonioglyphioceras)*. The Missourian-Virgilian sequence in the Conemaugh Group has yielded five ammonoid assemblages, which characterize the lower and upper Brush Creek limestone units (*Pennoceras*), the Carnahan Run and equivalent Portersville units *(Preshumardites),* and the Ames limestone unit *(Schistoceras).*

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10: Biostratigraphic Distribution of Appalachian Carboniferous Trilobites

David K. Brezinski

Introduction and Previous Investigations

Trilobites have long been recognized in Carboniferous strata of the Appalachian Basin. The earliest discussions of trilobites from the Carboniferous strata of the Appalachian Basin were those of Meek (1875), Claypole (1884a, b), Herrick (1887), and Vogdes (1887). These reports dealt mainly with the Lower Carboniferous of eastern Ohio. Herrick (1887) also described the Upper Carboniferous (Pennsylvanian) trilobite species *Phillipsia trinucleata*. Most of the published works subsequent to Herrick's works have dealt with Carboniferous trilobites as ancillary parts of other marine faunas (Hyde, 1953; Szmuc, 1970). Mark (1912) provided faunal lists of fossils, including trilobites, from various Upper Pennsylvanian localities. Morningstar (1922) enumerated localities that yielded the Pennsylvanian trilobite species *Ameura sangamonensis* and *Sevillia trinucleata* from Pottsville strata of eastern Ohio. Wilson (1979) named a new species of *Brachymetopus* from the Cuyahoga Formation of eastern Ohio. Many studies, too numerous to list here, have noted the presence of trilobites within larger marine faunas as parts of stratigraphic or paleoecological studies. More recently, Brezinski (1983, 1988) discussed species ranges, paleoecology, and taxonomy of *Paladin chesterensis* (Weller), as well as many of the other Carboniferous species of the northern part of the central Appalachian Basin. Brezinski and others (1989) detailed the distribution of Pennsylvanian trilobites from eastern Ohio.

Stratigraphic Distribution of Mississippian Trilobites

While trilobites from the Mississippian strata of the Appalachian Basin exhibit a recognizable stratigraphic segregation somewhat similar to the Mississippian trilobites of the Midcontinent, the relatively poorly known Appalachian forms cannot be separated into as many distinct and separate faunas as can the Midcontinent species (Brezinski, 2007). Just as the Midcontinent faunas exhibit distinctly different shallow-water and deep-water faunas, however, so too do the Appalachian species. Three Kinderhookian and Osagean Mississippian trilobite associations are recognized. These faunas are composed largely of endemic genera. There are two distinct Upper Mississippian faunas, one dominated by *Kaskia* and the other by *Paladin*. These different faunas tend to exhibit an onshore *(Kaskia)* to offshore *(Paladin)* segregation.

Kinderhookian

The best known Lower Mississippian (Tournaisian, Kinderhookian) trilobite fauna in the Appalachian Basin is present in the Waverly Group of eastern Ohio (Fig. 10.1). Faunal constituents of the lower formation, the Cuyahoga Formation, include *Brachymetopus nodosus* Wilson (Plate 10.1: Fig. 1), *Griffithidella waverlyensis* Hessler (Plate 10.1: Fig. 10), *Ameropiltonia eurybathrea* (Hessler) (Plate 10.1: Fig. 11), *Namuropyge cuyahogae* (Claypole), and *Australosutura lodiensis* (Meek) (Plate 10.1: Figs. 2–3).

The genera *Namuropyge, Brachymetopus,* and *Ameropiltonia* are known elsewhere in North America only from Kinderhookian strata. These other occurrences include the Chouteau Formation of Missouri (Brezinski, 1998, 2007; Kollar, 1997), Caballero Formation of New Mexico (Brezinski, 2000), and the lower Paine Member of the Lodgepole Formation of Montana. Thus, the similarity of trilobite genera suggests that the Cuyahoga is Kinderhookian in age.

Osagean

Within the Byers and Vinton Members of the Logan Formation, the upper formation of the Waverly Group, *Pudoproetus auriculatus* Hessler (Plate 10.1: Figs. 9, 12), and *Paladin marginatus* (Hyde) (Plate 10.1: Fig. 7) are present. Recent reexamination of the type material and study of additional material within the U.S. Geological Survey stratigraphic collections housed at the Denver Research Center indicates that *P. marginatus* is actually assigned to the common Osagean genus *Thigriffides*. *Thigriffides* is commonly associated with *Pudoproetus* within interpreted deep-water deposits of Texas, Oklahoma, and New Mexico (Brezinski, 1998, 2000). Both *Thigriffides* and *Pudoproetus* are commonly found in Osagean strata of the central and southwestern United States (Brezinski, 2007). Therefore, these trilobite genera suggest that the Logan Formation of the Waverly Group is Osagean in age. Matchen and Kammer (2006) confirmed this age determination largely based on brachiopod generic ranges.

Another Mississippian fauna is present within the late Osagean Fort Payne Formation of Tennessee, Kentucky, and Georgia (Fig. 10.1). This fauna consists of the genera *Australosutura georgiana* Rich (Plate 10.1: Figs. 4–5), an unnamed species of *Pudoproetus,* an unidentified species of *Phillibole* (Plate 10.1: Fig. 13), and a griffithidid species (Plate 10.1: Fig. 15) (Rich, 1966). This fauna is somewhat similar to that found in the prodeltaic facies of the Borden Delta of Kentucky (Kammer and others, 1986) and can be attributed to habitation in dys-

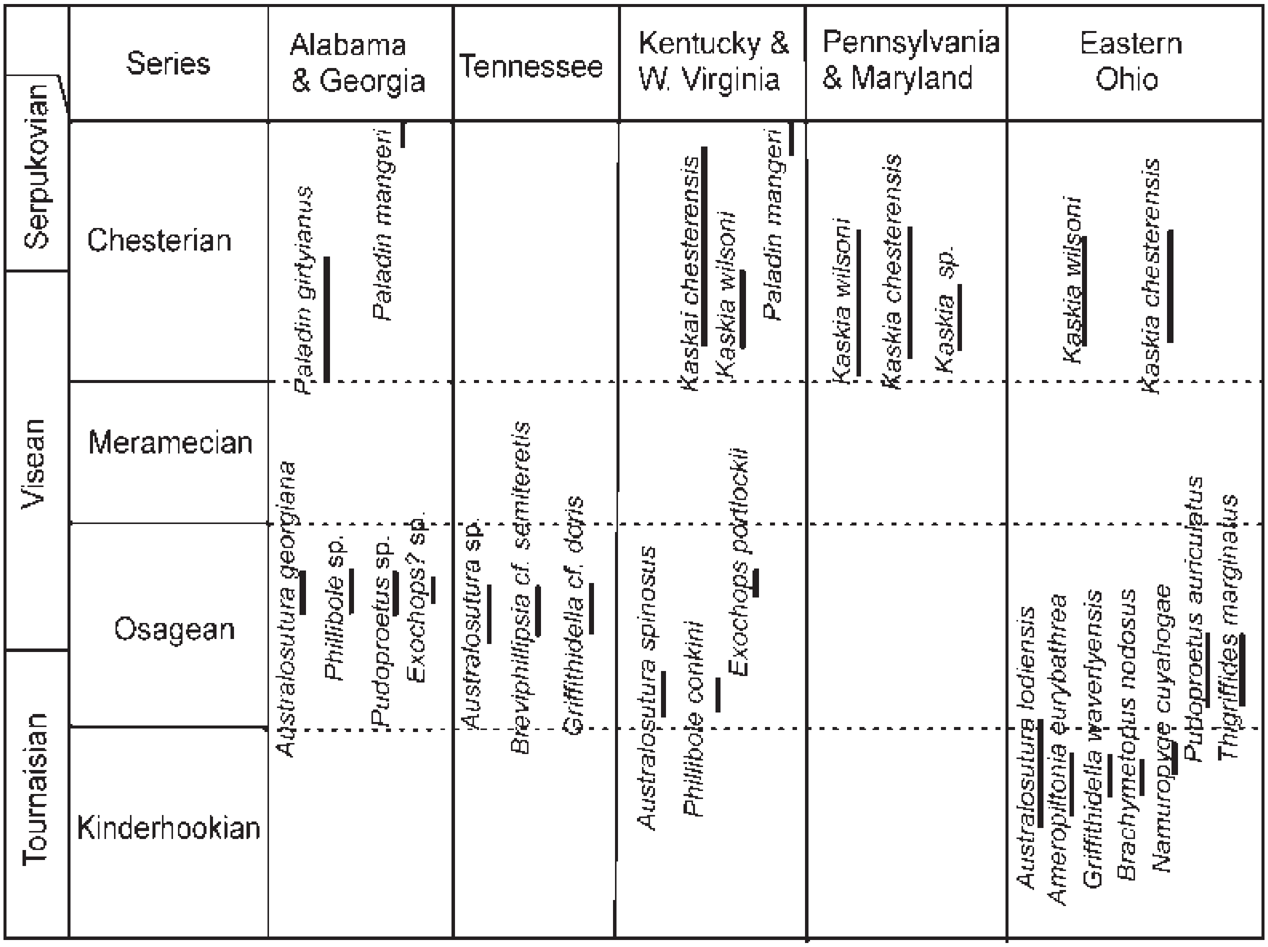

Figure 10.1. Range distribution of Mississippian trilobite species of the Appalachian Basin.

aerobic environments. Rich (1966) identified parts of this fauna in the Lavender Shale Member of the Fort Payne, and Englund (1968) found these genera in the Grainger Formation of Tennessee. This stratigraphic interval has been equated with the Maccrady Formation by Hasson (1986). Similar faunal components are known from Osagean deep-water deposits of Texas, Oklahoma, and southeastern Illinois (Brezinski, 1998). *Exochops portlockii* has been identified within collections in the U.S. National Museum from the Fort Payne Formation of southern Kentucky. Likewise, the unidentified griffithidid species illustrated by Rich (1973) exhibits a strong resemblance to and is very likely *Exochops*. Species of *Exochops* are known from middle to late Osagean strata of the central and southern Midcontinent (Brezinski, 2007).

Mississippian trilobites are also present in the Maccrady Formation of southwestern Virginia and eastern Tennessee (Fig. 10.1). The most common species are *Australosutura* sp. (Plate 10.1: Fig. 6), *Breviphillipsia* cf. *B. semiteretis* Hessler (Plate 10.1: Fig. 8), and *Griffithidella* cf. *G. doris* (Plate 10.1: Fig. 14). This poorly preserved fauna bears strong generic and specific resemblance to that found in the Burlington Formation of Missouri and the Lake Valley Formation of New Mexico (Brezinski, 2000, 2007). Consequently, the intervals of the Maccrady Formation that have yielded trilobites can be interpreted as mid-Osagean in age.

Chesterian

Unlike the modest generic diversity exhibited in the Kinderhookian and Osagean trilobite faunas of the Appalachian Basin, the Chesterian is represented by only two genera, *Paladin* and *Kaskia*. These genera are typical of the Late Mississippian of North America (Brezinski, 2003). Two specific associations can be recognized in the Late Mississippian strata of the Appalachian and Black Warrior Basins. Although different trilobite associations in the Kinderhookian and Osagean are generally stratigraphic in nature, the Late Mississippian associations appear to be geographic in origin (Fig. 10.1).

In the northern part of the Appalachian Basin, the species assignable to *Kaskia* such as *K. chesterensis*, *K. wilsoni*, and an undescribed species, are present (Plate 10.1: Figs. 16–21). These species are present in the Maxville Limestone of eastern Ohio, the Wymps Gap Limestone of the Mauch Chunk Formation of Pennsylvania, and the Greenbrier Formation of Maryland and northern West Virginia (Brezinski, 1988). Both *Kaskia chesterensis* (Weller) (Plate 10.1: Figs. 16–17) and *K. wilsoni* (Plate 10.1: Figs. 20–21) are present in most early Chesterian marine units. The stratigraphically highest observed occurrence of *K. chesterensis* was from the Hinton Formation (upper Chesterian, Serpukovian) from southern West Virginia (Fig. 10.1). *Kaskia chesterensis* and *K. wilsoni* are known elsewhere in the United States from the lower Chesterian of Illinois and Iowa (Brezinski, 2003).

In the southern part of the basin, and in coeval strata of the Black Warrior Basin, the most pervasive Late Mississippian trilobite species is *Paladin girtyianus* (Fig. 10.1; Plate 10.1: Figs. 22–23). This species is present in the Monteagle Limestone, Hartselle Sandstone, Pride Mountain Shale, and Bangor Limestone, a range that spans most of the lower and middle Chesterian. This species is also present in the Fayetteville and Pitkin Formations of Arkansas and Oklahoma.

The uppermost Chesterian contains a *Paladin* species assigned to *P. morrowensis* by Gordon and Henry (1981). This species is found in the Bramwell Formation of West Virginia and the Parkwood Formation of Alabama and appears to span the Mississippian-Pennsylvanian boundary (Fig. 10.2; Plate 10.1: Figs. 24–25). This species is synonymous with *Paladin mangeri* Brezinski, a recently erected species known from the Morrowan Brentwood Limestone of Arkansas (Brezinski, 2008).

Stratigraphic Distribution of Pennsylvanian Trilobites

Brezinski (1999), based on generic composition, subdivided the stratigraphic distribution of Pennsylvanian trilobites of the United States into three units. The lowest unit, spanning the Morrowan to earliest Desmoinesian, contains the genus *Sevillia* and its component species, *S. trinucleata* and *S. sevillensis* (Fig. 10.2). The second unit is made up strictly of *Ditomopyge scitula* (Newell) and *Ameura missouriensis* (Meek and Worthen) and spans the Desmoinesian and Missourian (Fig. 10.2). The last unit, spanning the Virgilian, is composed of *Ditomopyge decurtata* (Fig. 10.2).

The Early Pennsylvanian *Sevillia* fauna in the Appalachians is best recognized in the Pottsville Formation of eastern Ohio (Brezinski, 1988; Brezinski and others, 1989). The earliest recognized occurrence of *Sevillia* is *S. trinuceata* (Herrick) from the Sharon (Morrowan) marine interval. This species ranges upward into the early Desmoinesian Zaleski marine interval of the Allegheny Group. *Sevillia sevillensis* Weller (Plate 10.1: Fig. 26) is known only from the Atokan Lower Mercer marine interval of the Pottsville in Ohio (Brezinski, 1988; Brezinski and others, 1989). *Sevillia trinucleata* (Plate 10.1: Fig. 27) also occurs in the Atokan Kendrick Shale Member (=Dingess Shale) of the Breathitt Group of eastern Kentucky (Zei, 1991).

Perhaps the most pervasive and long-ranging Pennsylvanian trilobite species in North America is *Ditomopyge scitula* (Meek and Worthen) (Plate 10.1: Figs. 28–29). In the Appalachians, this species is known from Morrowan through Missourian deposits (Fig. 10.2). Its earliest Appalachian occurrence is within the Morrowan

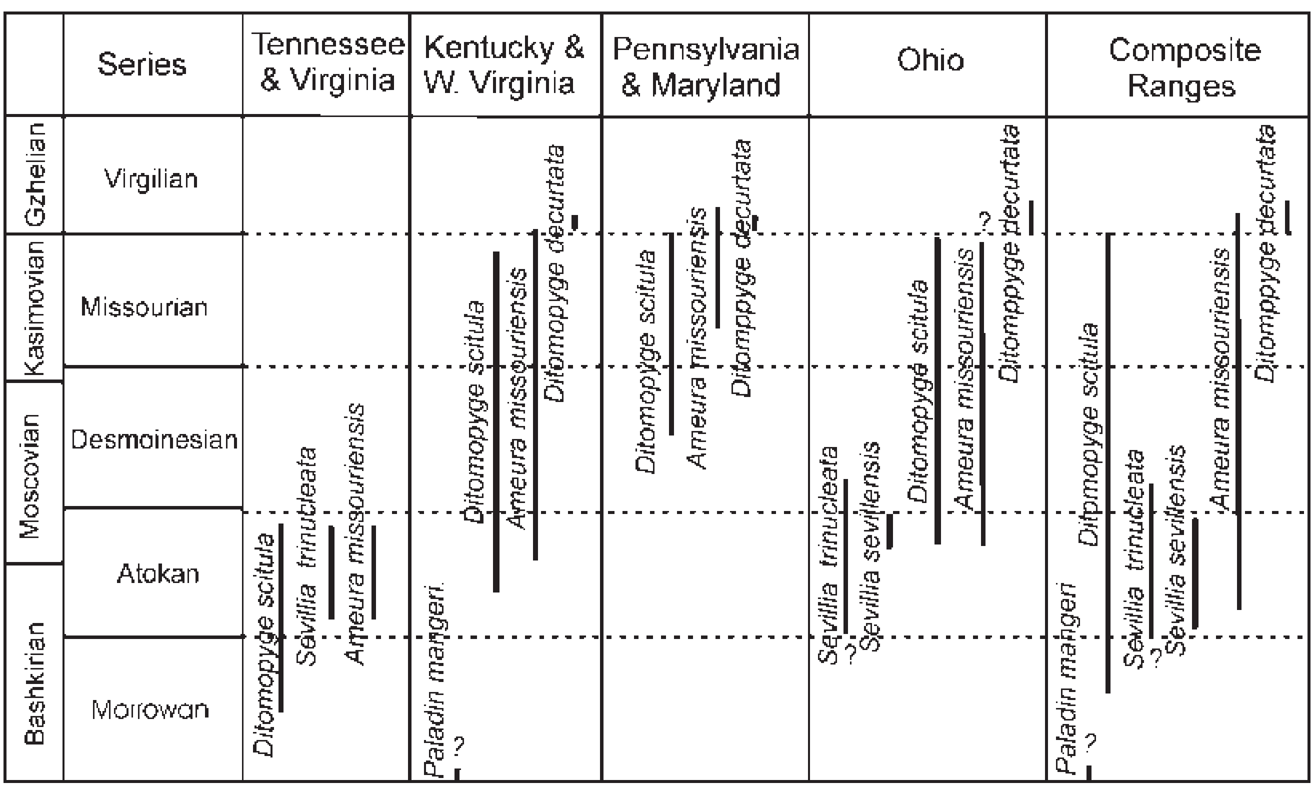

Figure 10.2. Stratigraphic ranges of Pennsylvanian trilobite species of the Appalachian Basin.

Dorton marine interval of the upper Lee Formation (Zei, 1991). This species also is recorded in the Atokan Eagle, Kendrick, and Magoffin marine members of eastern Kentucky and West Virginia (Price, 1915, 1916, 1921; Zei, 1991). This species is found in the Lower and Upper Mercer marine intervals of the Pottsville Formation and nearly all Allegheny marine intervals of eastern Ohio (Brezinski, 1988; Brezinski and others, 1989). *Ditomopyge scitula* occurs in all Missourian Glenshaw Formation marine intervals of the Conemaugh Group of eastern Ohio, western Pennsylvania, Maryland, and northern West Virginia (Brezinski, 1988).

Although *Ameura missouriensis* (Shumard) (Plate 10.1: Figs. 30–31) is long-ranging like *Ditomopyge scitula* (Fig. 10.2), it is not nearly as pervasive, occurring in fewer Pennsylvanian marine intervals of the Appalachian Basin and displaying a more localized distribution. Its earliest recorded occurrence is within the Atokan Magoffin marine interval of eastern Kentucky (Zei, 1991). It is uncommon in the Lower Mercer marine interval of eastern Ohio (Brezinski, 1988; Brezinski and others, 1989). *Ameura missouriensis* is also known from the Desmoinesian Zaleski and Washingtonville marine intervals of the Allegheny Formation of eastern Ohio, and the Missourian Brush Creek, Cambridge (=Pine Creek), and Portersville (=Woods Run) marine intervals of eastern Ohio, Pennsylvania, Maryland, and northern West Virginia (Price, 1914; Brezinski, 1988; Brezinski and others, 1989).

Perhaps the most stratigraphically useful Pennsylvanian trilobite species is *Ditomopyge decurtata* (Gheyselinck). In the Appalachian Basin this species is found only in the Ames and Skelley marine units, which mark the base of the Virgilian Series (Fig. 10.2). The specimens of *Ditomopyge decurtata* found in the Appalachian Basin (Plate 10.1: Figs. 32–33) are much smaller than those found in the Midcontinent region of the United States. This species is also found in Virgilian marine strata of Oklahoma and Kansas.

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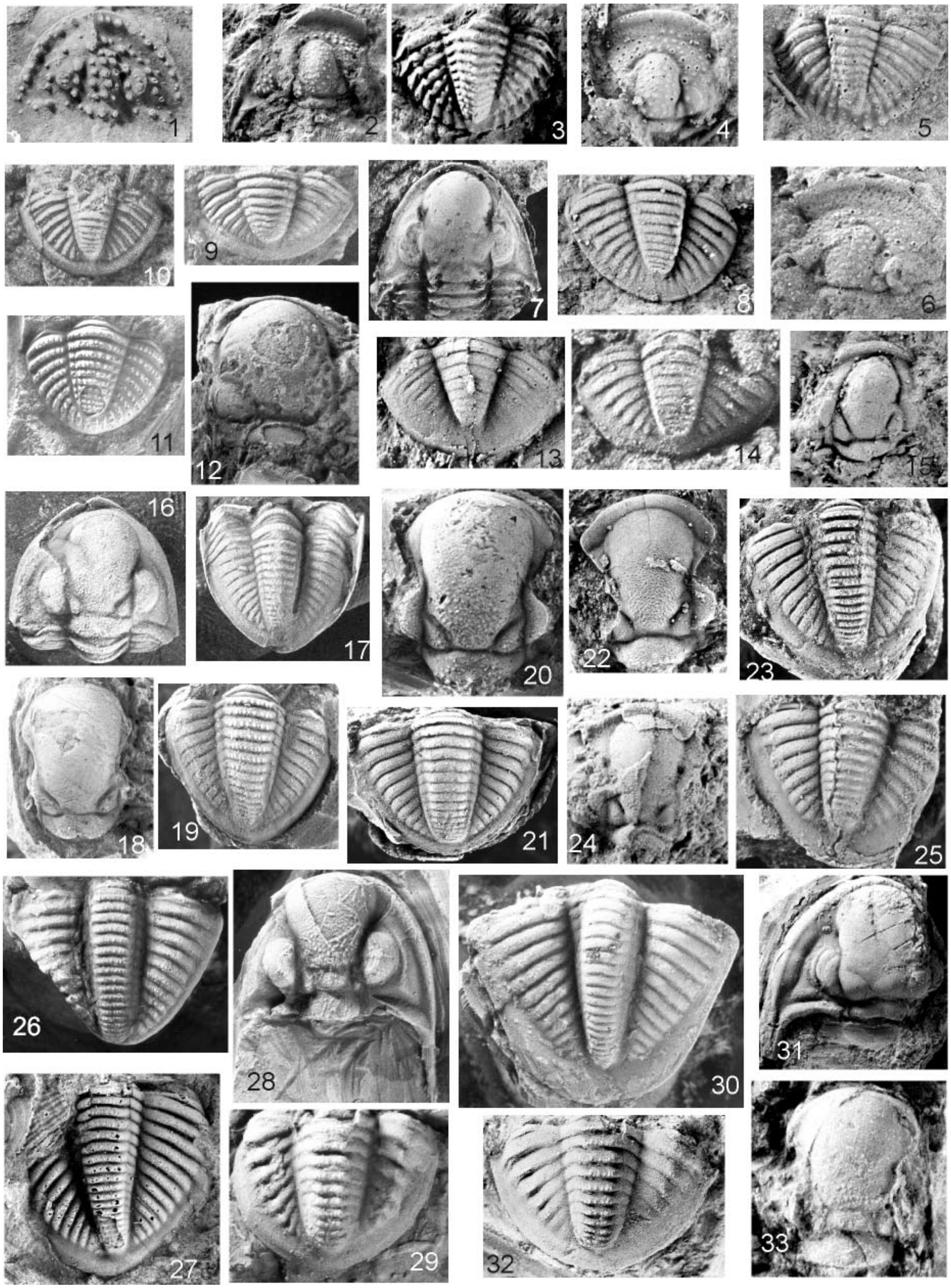
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Plate 10.1. 1. *Brachymetopus nodosus* Wilson, Cuyahoga Formation, Ohio. 2, 3. *Australosutura lodiensis* (Meek), Cuyahoga Formation, Ohio. 4, 5. *Australosutura georgiana* Rich, Fort Payne Formation, Georgia. 6. *Australosutura* sp., Maccrady Formation, Tennessee. 7. *Thigriffides marginatus* (Hyde). 8. *Breviphillipsia* c.f. *B. semiteretis* Hessler, Macrady Formation, Tennessee. 9, 12. *Pudoproetus auriculatus* Hessler, Cuyahoga Formation, Ohio. 10. *Griffithidella waverlyensis* Hessler, Cuyahoga Formation, Ohio. 11. *Ameropiltonia eurybathrea* (Hessler), Cuyahoga Formation, Ohio. 13. *Phillibole?* sp., Fort Payne Formation, Georgia. 14. *Griffithidella doris*, Macrady Formation, Tennessee. 15. *Griffithidella?* sp., Fort Payne Formation, Georgia. 16, 17. *Kaskia chesterensis* (Weller), Wymps Gap Limestone, Maryland. 18, 19. *Kaskia* sp., Wymps Gap Limestone, Pennsylvania. 20, 21. *Kaskia wilsoni*, Wymps Gap Limestone, Pennsylvania. 22, 23. *Paladin girtyianus* Hahn and Hahn, Bangor Formation, Alabama. 24, 25. *Paladin mangeri* Brezinski, Parkwood Formation, Alabama. 26. *Sevillia sevillensis* (Weller), Pottsville Formation, Ohio. 27. *Sevillia trinucleata* (Herrick), Pottsville Formation, Ohio. 28, 29. *Ditomopyge scitula* (Meek and Worthen), Allegheny Formation, Ohio. Ohio. 30, 31. *Ameura missouriensis* (Shumard) Allegheny and Glenshaw Formation, Ohio; *Ditomopyge decurtata* (Gheyselinck), Glenshaw Formation, Ohio and West Virginia, respectively.

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11: Carboniferous Echinoderm Succession In the Appalachian Basin

Frank R. Ettensohn, William I. Ausich, Thomas W. Kammer, Walter K. Johnson, and Donald R. Chesnut Jr.

Introduction

By Carboniferous time, many echinoderm groups had experienced an expansion in diversity and abundance. In fact, no period in earth history compares to the Mississippian or Lower Carboniferous for diversity and abundance of echinoderm remains. The echinoderm classes Crinoidea and Blastoidea attained peak abundances during this time, and echinoids became locally abundant for the first time. Crinoid remains in particular are so abundant in many limestones of the period that the Mississippian has been called the Age of Crinoids.

The first formal use of echinoderms for zonation of Carboniferous rocks in North America was by Stuart Weller (1926), who used crinoids and blastoids as the basis for five of his 14 Mississippian zones. The zones, however, were largely restricted to the type Mississippian section of the Illinois (or Eastern Interior) Basin, but some of the more prominent zones were carried into the Appalachian Basin (e.g., Cooper, 1948). Even at present, however, use of these zones in the Appalachian Basin has not been well corroborated with biostratigraphy based on other organism groups.

The Carboniferous section in the Appalachian Basin can generally be divided into a three-part lithologic succession, including Lower to mid-Mississippian (Tournaisian–lower Viséan) clastics, Mid- to Upper Mississippian (upper Viséan) carbonates, and Upper Mississippian through Pennsylvanian (upper Viséan–Gzelian) clastics. Although echinoderms have been reported from nearly every part of the Appalachian section, they are clearly most abundant and diverse in the Middle and Upper Mississippian carbonates, and they decline markedly in both abundance and diversity in uppermost Mississippian and Pennsylvanian parts of the section.

The role of depositional facies is of particular significance in the evolution of echinoderms. Early Mississippian echinoderms were especially well adapted to carbonate environments, as epitomized by the diverse and abundant crinoid and blastoid faunas of the Hampton, Gilmore City, Burlington, and Keokuk limestones of the Illinois Basin (Bassler and Moodey, 1943). During Early Mississippian time, however, undoubtedly as a response to environmental changes, echinoderm faunas evolved diverse and abundant communities in siliciclastic facies, such as the late Osagean faunas of the Borden Group at Crawfordsville, Ind. (Van Sant and Lane, 1964). The Appalachian Basin faunas are significant because they record the earliest known Mississippian faunas to make this shift from carbonate- to clastic-dominated sediments. These faunas were noted in the Cuyahoga Formation of northeastern Ohio (Hall and Whitfield, 1875; Roesor, 1986) and in the Nada Member of the Borden Formation of northeastern Kentucky (Lane and Dubar, 1983; Li, 2000).

Although there has been substantial recent work on Carboniferous echinoderms in the Appalachian Basin and nearby areas, there has been little work on their use as diagnostic, zonal indicators. Hence, this report is essentially a survey based on earlier faunal studies, and we have noted as diagnostic below and in Figure 11.1 only those forms that are clearly identified and appear to be relatively common across large parts of the basin. We consider faunas extending as far west as the Cumberland Saddle of Kentucky and Tennessee to be within the Appalachian Basin.

Mississippian Succession

Kinderhookian

Kinderhookian (lower Tournaisian) rocks in the Appalachian Basin consist largely of basinal, black or dark gray shales in the Sunbury or Chattanooga Shales, deposited in deeper anoxic to dysoxic conditions, and wherever they occur, faunas of any sort are extremely rare.

Kinderhookian-Osagean Transition

During the Kinderhookian-Osagean transition (middle to late Tournaisian), sedimentary facies in the Appalachian Basin were dominated by westward-prograding, post-Acadian siliciclastic wedges that extended into the Illinois Basin. The most prominent and extensive of these wedges was the Borden deltaic complex, which prograded from the east and northeast. This complex includes shales, mudstones, siltstones, and sandstones deposited in basinal, prodelta, and delta-front environments represented by the Borden Formation of eastern Kentucky, the Logan and Cuyahoga formations of Ohio, the Price-Pocono formations of West Virginia, Virginia, Maryland, and Pennsylvania, and the Grainger Formation of eastern Tennessee and southeastern Kentucky.

Although echinoderm faunas of this age are rare in the Appalachian Basin, a few faunas are known. The oldest Mississippian echinoderm fauna in the Appalachian Basin is from the Cuyahoga Formation, first comprehensively described by Hall and Whitfield

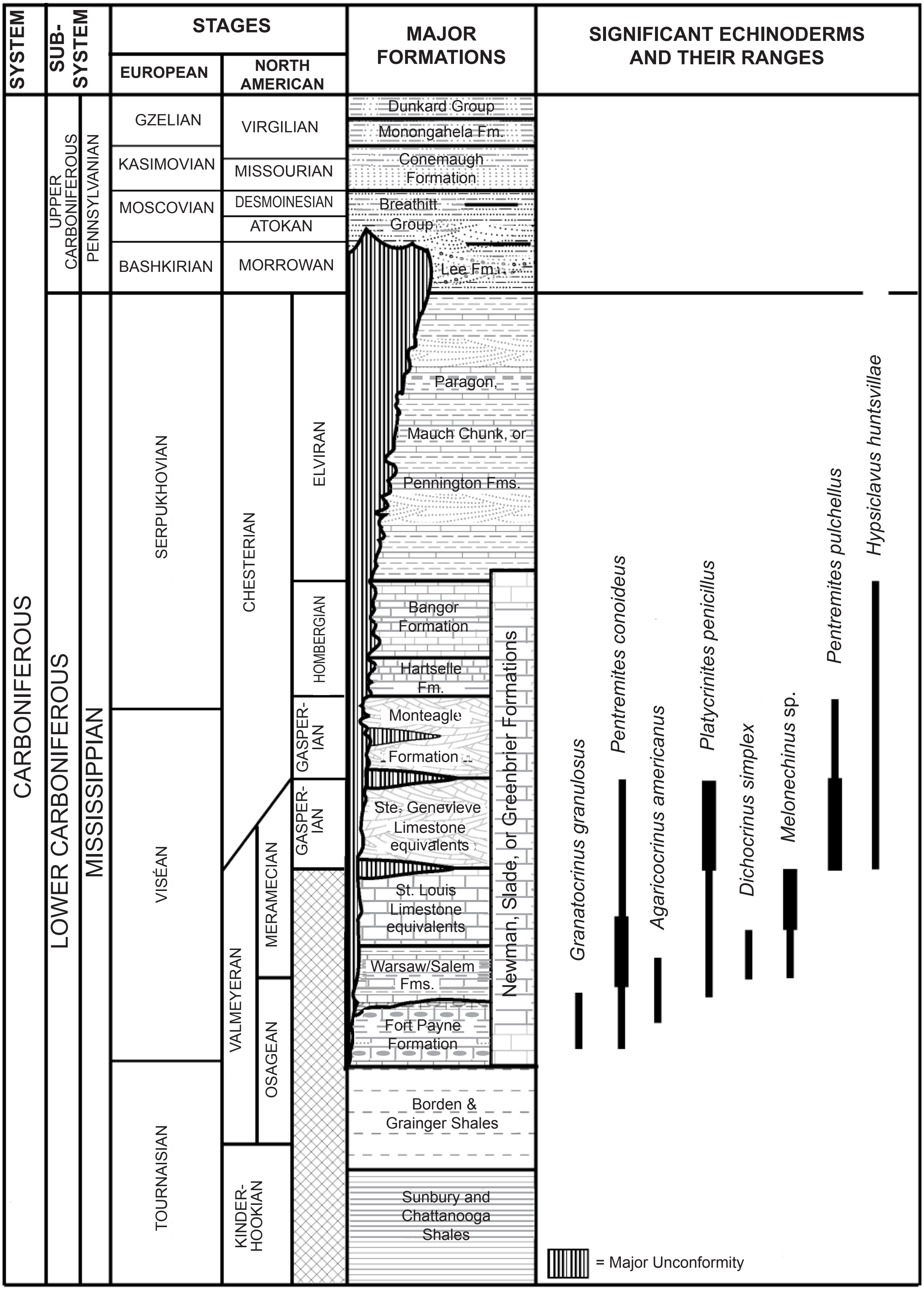

Figure 11.1. Stratigraphic distribution of diagnostic Carboniferous echinoderms in the Appalachian Basin. The representation of stages is not necessarily proportional to the time they represent. Continued on next page.

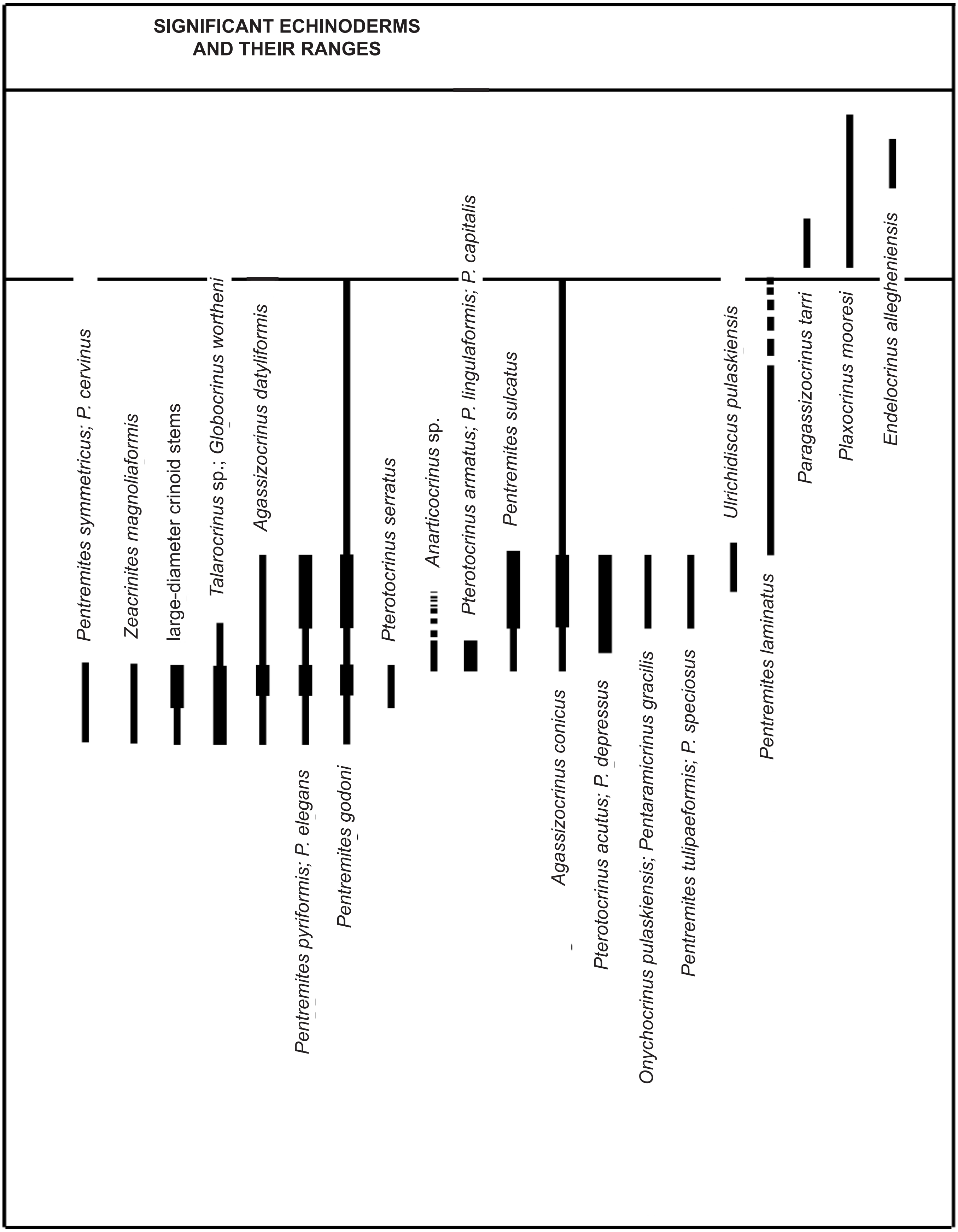

Figure 11.1. Stratigraphic distribution of diagnostic Carboniferous echinoderms in the Appalachian Basin. The representation of stages is not necessarily proportional to the time they represent. Continued from previous page.

(1875) and more recently revised by Roeser (1986). The age of the Cuyahoga Formation has been equivocal for many years, but it is now generally regarded that the Kinderhookian-Osagean boundary is present within this formation. Thus, the Cuyahoga crinoid fauna is considered to be of Kinderhookian–early Osagean age here. This fauna is regarded to contain nearly 25 species, with more than 67 percent of the specimens recovered by Roeser (1986) belonging in five species: *Aorocrinus helice, Cusacrinus helice, Cusacrinus daphne, Forbesiocrinus communis,* and *Amphoracrinus viminalis.* Unfortunately, these are all endemic species, so the crinoids offer little biostratigraphic insight for the Cuyahoga Formation, other than confirming a late Kinderhookian to early Osagean age.

Middle through Late Osagean

By middle to late Osagean (early Viséan) time, Borden clastic sedimentation declined substantially in southern and western parts of the basin. This was a period of delta destruction and abandonment, and although echinoderms are relatively uncommon, notable exceptions are the Nada Member of the Borden Formation from eastern Kentucky and the Fort Payne Formation of the Cumberland Saddle area in south-central Kentucky and adjacent parts of Tennessee.

The Nada Member is the uppermost member of the Borden Formation and is a mixed carbonate-clastic facies that has been interpreted to represent delta destruction. The fauna in the unit has been studied by Lane and Dubar (1983) and Li (2000). Age determination for the Borden Formation in northeastern Kentucky has also been problematic, with various ages indicated by different fossil groups in various members of this unit. The crinoids in the Nada Member are characteristic Osagean crinoids, and more specifically, this fauna contains eight species that are known only from the Nada Member and the upper part of the Burlington Limestone in Illinois, Iowa, and Missouri (Li, 2000). These diagnostic, middle Osagean species include the camerates *Dorycrinus quinquelobus, Gilbertsocrinus tuberculosus, Macrocrinus konincki, Platycrinites glyptus, Platycrinites tenuibrachiatus,* and *Rhodocrinites barrisi,* and the disparids *Halysiocrinus dactylus* and *Synbathocrinus wortheni*. The most common Nada crinoid species is *Uperocrinus pyriformis*. This species is not confined to the middle Osagean, but it is characteristic of the fauna of the upper part of the Burlington Limestone.

After middle to late Osagean delta abandonment, deeper-water cherty carbonates and carbonate-rich clastics of the Fort Payne Formation infilled the basin seaward of the abandoned delta front, so that the Fort Payne Formation predominates in this interval throughout southern and southwestern parts of the Appalachian Basin. Carbonate buildups and mud mounds are locally common in the Fort Payne, and some of the echinoderm species noted below comprise important parts of the mud-mound faunas. Late Osagean crinoid faunas are well represented in the Fort Payne Formation of Tennessee, Kentucky, and Alabama. Crinoidal remains dominate several Fort Payne facies, and crinoid calyxes and blastoid thecae may be well preserved and relatively abundant. Crinoid faunas were initially reported in the Fort Payne from Tennessee in 1849 by Gerard Troost, and they were recognized then as being late Osagean in age (correlative with the Keokuk Limestone of the Mississippi River Valley section) (e.g., Bassler, 1926). Modern systematic study of Fort Payne echinoderms is under way and seems to verify this age assignment for Fort Payne crinoids in south-central Kentucky. Fort Payne crinoids that are restricted to other late Osagean faunas include the camerate genus *Alloprosallocrinus* and the following species: camerates *Abatocrinus grandis, Abatocrinus stereopes, Agaricocrinus crassus, Dorycrinus gouldi, Alloprosallocrinus conicus, Eretmocrinus magnificus, Gilbertsocrinus tuberosus, Uperocrinus nashvillae*, and *Uperocrinus robustus;* cyathocrinine cladids *Cyathocrinites asperrimus, Cyathocrinites glenni*, and *Barycrinus stellaltus;* disparid *Catillocrinus tennesseeae;* flexibles *Gaulocrinus bordeni, Metichthyocrinus tiaraeformis, Nipterocrinus monroensis, Taxocrinus colletti,* and *Wachsmuthicrinus spinosulus* (Meyer and others, 1989; Ausich and Meyer, 1992, 1994; Ausich and others, 1994, 1997; Meyer and Ausich, 1997). Although *Agaricocrinus americanus* does occur in both middle and upper Osagean strata in the Mississippi River Valley (Meyer and Ausich, 1997), it is common and characteristic of upper Osagean strata in the Appalachian Basin and Midcontinent (Fig. 11.1).

Ausich and Meyer (1988) reported a diverse but largely endemic blastoid fauna in the Fort Payne Formation of south-central Kentucky, so it is of little use for regional biostratigraphy. The exception was *Granatocrinus granulosus,* which is also known from the late Osagean New Providence Shale Member of the Borden Formation in north-central Kentucky (Fig. 11.1). Moreover, blastoids from the Fort Payne of Georgia, described as *Pentremites cavus* by Allen and Lester (1954), are actually among the earliest forms of the diagnostic species *P. conoideus* (Fig. 11.1).

Overall, well-preserved Kinderhookian and Osagean echinoderm faunas are very rare in the Appalachian Basin. In some cases, however, the occurrence of echinoderms, with reference to crinoids in the Mississippi River Valley section (Laudon, 1973), can aid in constraining the age of Appalachian Basin strata. In the eastern United States, a number of crinoid genera are either typical of or restricted to Osagean time. Camerate crinoids, such as *Aorocrinus, Abatocrinus, Actinocrinites, Alloprosallocrinus, Agaricocrinus, Azygocrinus, Dizgocrinus, Dorycrinus, Eretmocrinus, Eutrochocrinus, Macrocrinus,* and *Uperocrinus*, are characteristic of the Osagean. Of these, *Azygocrinus* occurred only during middle Osagean time and *Alloprosallocrinus* occurred only during late Osagean time (Fig. 11.1).

Meramecian

By Meramecian (middle Viséan) time, the Appalachian Basin was filled with post-Acadian deltaic clastics or deeper-water Fort Payne carbonates and clastics, and a transition to shallow-water, carbonate deposition was ongoing. The Meramecian was characterized by a widespread, eastward transgression that produced a gradual onlap of carbonates over Kinderhookian-Osagean clastics.

One of the most remarkable changes in echinoderm faunas at the Osagean-Meramecian boundary is the disappearance of camerate crinoids with large, many-plated calyxes (Laudon, 1948) and their subsequent replacement by cladid inadunates and smaller, more simply plated camerate crinoids that were cladid homeomorphs (Waters and others, 1993). In the lower Meramecian Warsaw-Salem interval, one of these cladid homeomorphs, *Dichocrinus simplex,* is the only diagnostic crinoid (Bassler and Moodey, 1943) (Fig. 11.1). In the older literature, *D. simplex* was commonly identified as *Talarocrinus simplex*, but in work by Burdick and Strimple (1982), the species was referred back to the genus *Dichocrinus*. Other diagnostic indicators of the Warsaw-Salem interval include the blastoids *Mesoblastus wortheni*, *Tricoelocrinus,* and *Pentremites conoideus* (Fig. 11.1). *Pentremites conoideus*, in particular, attained its peak abundance in the Warsaw-Salem interval. Although more diagnostic of the St. Louis, the echinoid *Melonechinus*, also known by the junior synonym *Melonites*, made its first appearance in the Appalachian Basin in the Warsaw-Salem interval (Butts, 1926) (Fig. 11.1).

Another diagnostic crinoid that first makes its appearance in the Warsaw-Salem interval of the Appalachian Basin is *Platycrinites penicillus* (Dever and Moody, 1979; Dever, 1999), also known as *P. huntsvillae* or *Platycrinus penicillus*. Although the occurrence of this crinoid is the basis for the *P. penicillus* Zone of Weller (1926), and it is commonly thought to be diagnostic only of the Ste. Genevieve and its equivalents, the range of this crinoid extends back to the Warsaw-Salem, St. Louis, and their equivalents (Fig. 11.1). In the Appalachian Basin, the first occurrence of *P. penicillus* is normally reported from upper St. Louis equivalents, but in south-central Kentucky, its first appearance is even earlier (Dever and Moody, 1979; Dever, 1999).

In upper Meramecian St. Louis equivalents (e.g., Hillsdale and Tucumbia formations), the echinoid *Melonechinus* attains its peak abundance (Fig. 11.1), and spines of the long-ranging echinoid genus *Archaeocidaris* also become especially abundant in lower parts of the unit.

Chesterian

The Ste. Genevieve and its equivalents (e.g., Denmar and lower Monteagle formations), long considered to be latest Meramecian in age, are now commonly regarded as earliest Chesterian (Genevievian) in age (Maples and Waters, 1987). This part of the Chesterian Stage (upper Viséan-Serpukhovian) generally reflects very shallow-water, commonly oolitic environments that represent the culmination of Meramecian uplift and shallowing across the southern flank of the continent. Although Genevievian rocks may locally contain several endemic crinoid species, *P. penicillus* is clearly the most diagnostic crinoid species throughout the entire basin. In addition, the blastoid *Pentremites pulchellus*, which is synonymous with *P. princetonensis*, *P. tuscumbiae*, *P. pediculatus*, and *P. arctibrachiatus* (Horowitz and others, 1981), was thought to occur only in Genevievian rocks in the Appalachian Basin, but in Alabama the species also apparently ranges into rocks of Gasperian age (Bassler and Moodey, 1943) (Fig. 11.1). Moreover, the highest occurrence of *Pentremites conoideus* is in the Genevievian rocks of Alabama (Bassler and Moodey, 1943) (Fig. 11.1).

Post-Genevievian, lower Chesterian, or Gasperian rocks in the Appalachian Basin are largely high-energy, oolitic, and bioclastic calcarenites, which may be difficult to distinguish lithologically from underlying Genevievian rocks. In the older literature these rocks are commonly designated as the "Gasper Formation," and in places an unconformity or paleosol may separate Genevievian and Gasperian rocks. The boundary is usually subtle, however, and is more easily identified by changes in echinoderm fauna than in lithology. Most important, *P. penicillus* leaves the section and is replaced by various species of *Talarocrinus*, which are reported only from post-Genevievian, Gasperian rocks across the eastern and central United States. Although *Talarocrinus* is supposedly restricted to Gasperian rocks, the genus has been reported from shaly carbonates just below the Fido Sandstone in Virginia (Butts, 1927), an undescribed species is known from rocks of similar age in northeastern Kentucky, and Burdick and Strimple (1982) indicated that in Alabama *Talarocrinus* occurs just below the *Agassizocrinus conicus* Zone, which begins in mid-Hombergian Glen Dean equivalents. These three occurrences indicate that in the Appalachian Basin, *Talarocrinus* also occurs in post-Gasperian, Golconda-equivalent, lower Hombergian rocks (Fig. 11.1). *Globocrinus wortheni* apparently has the same range as *Talarocrinus* in the Appalachian Basin (Butts, 1927, 1940; Horowitz and Strimple, 1974). An unidentified "large crinoid stem" up to an inch in diameter and *Zeacrinites magnoliaformis* are wholly Gasperian in age, however (Fig. 11.1). The "large crinoid zone" has its peak occurrence in uppermost Gasperian units (Reelsville–Beech Creek, Tygarts Creek, Union Members), but is also present locally in lower parts of the Gasper (Fig. 11.1). Chesnut (2007) has recently suggested that this large crinoid stem may belong to the genus *Rhabdocrinus.*

The *P. penicillus*–*Talarocrinus* change is the basis for two major Mississippian zones (Weller, 1926), and the fact that both forms occur in similar lithologies indicates that the boundary is not facies-controlled, but instead approaches a true temporal plane (Swann, 1963). This change coincides with a time of major reorganization of echinoderm communities as more large, endemic camerates dropped out, cladids became dominant, cladid-homeomorph camerates like *Talarocrinus*, *Pterotocrinus*, *Dichocrinus*, *Hyrtanecrinus*, *Strimplecrinus*, and *Camptocrinus* became more prevalent, and the blastoid *Pentremites* became extremely abundant (Waters and Maples, 1991; Waters and others, 1993).

Agassizocrinus and *Pterotocrinus* are two other crinoids that are wholly indicative of the Chesterian, and both first appear in Gasperian rocks (e.g., Sutton, 1934; Horowitz and Strimple, 1974). *Agassizocrinus* is a unique stemless cladid crinoid that was common in high-turbulence, Chesterian environments. Its fused infrabasal cones were easily transported and preserved in many different environments, making them useful biostratigraphic indicators (Ettensohn, 1975). Cone shape in life, however, was apparently subject to great phenotypic variation, and the genus is probably oversplit based on these variations. Despite the many species, the low-coned *A. dactyliformis*, which is probably synonymous with *A. laevis* and *A. lobatus,* is the most diagnostic form in lower and middle Chesterian rocks. Although it is apparently common in all Gasperian rocks in the Illinois Basin, it is relatively rare in the Appalachian Basin. However, it is present in lower Gasperian rocks, reaches its peak occurrence in uppermost Gasperian rocks (Reelsville–Beech Creek, Tygarts Creek, Union Members) and lowermost Hombergian Golconda equivalents, and is common through late Hombergian Glen Dean equivalents (Bangor, Poppin Rock, and Lower Bluefield) (Fig. 11.1). On the other hand, the high-coned *A. conicus* is the basis for the *A. conicus* Zone of Burdick and Strimple (1982), which ranges from the mid-Hombergian Hartselle through the Bangor and its equivalents, and probably through the rest of the Chesterian Series (Paragon and Pennington Formations) (Fig. 11.1).

Pterotocrinus is an unusual camerate crinoid that had five elongated, tegminal “wing plates” extending outward from the crown at the level of the arms; it was the basis for two Upper Mississippian zones (Weller, 1926). Crowns and calyxes are rarely preserved, but the resistant, single-piece wing plates were commonly preserved and easily transported. The shape of these plates is commonly the basis for species designation (Sutton, 1934). Like *Agassizocrinus* infrabasals, *Pterotocrinus* wing plates were also apparently subject to great phenotypic variation, however, and as a result the genus is probably oversplit. Although Chesnut and Ettensohn (1988) synonymized several Hombergian species based on comparison of complete crowns and calyxes, some of the “form species” may still be useful for detailed, local biostratigraphy. In the Appalachian Basin, *Pterotocrinus* first appears as *P. serratus* in the upper Gasperian rocks of Virginia, West Virginia, and Alabama (Fig. 11.1), but they are apparently uncommon. In lower Hombergian Golconda equivalents at various places in the basin, *P. armatus*, *P. lingulaformis*, and *P. capitalis* are diagnostic, whereas in upper Hombergian Glen Dean equivalents, *P. acutus* (=*P. bifurcatus* and *P. spatulatus*) and *P. depressus* (=*P. wetherbyi*, *P. menardensis*, *P. clorensis*, *P. cuneatus*, and *P. vannus*) are characteristic (Fig. 11.1). The range of *P. depressus*, however, probably extends throughout overlying parts of the Chesterian Series as well (Fig. 11.1).

Several other crinoid species could be cited as indicative of the Chesterian Series, but most seem to be locally endemic and not particularly useful across large parts of the Appalachian Basin. A few less common forms with more widespread distribution include *Anartiocrinus*, a Hombergian genus, as well as *Onychocrinus pulaskiensis* and *Pentaramicrinus gracilis*, which are restricted to upper Hombergian Glen Dean equivalents (Fig. 11.1).

The blastoid genus *Pentremites* became especially abundant and diverged into several species by Gasperian time (Galloway and Kaska, 1957), but apparent diversity has also been superficially increased by oversplitting based on minor characters (Horowitz and others, 1981; Chesnut and Ettensohn, 1988). Using current literature and synonymies, 10 reported species appear to have diagnostic value in the Chesterian Series of the Appalachian Basin (Fig. 11.1). *P. godoni* (=*P. biconvexus*, *P. florealis*, and *P. planus*) apparently ranges through the entire post-Genevievian Chesterian in the basin, whereas *P. symmetricus* (=*P. welleri*, *P. altus*, *P.abruptus*, *P decipiens*, and *P. buttsi*) and *P. cervinus* are Gasperian species. On the other hand, *P. pyriformis* (=*P. patai*, *P. arctibrachiatus huntsvillensis, P. pyrimidatus*, *P. lyoni*, and *P. girtyi*) and *P. elegans* (=*P. canalis*) range through the Gasperian and Hombergian. *P. sulcatus* (=*P. cherokeeus*, *P. angularis*, *P. macalliei*, *P. serratus*, and *P. spicatus*) is a wholly Hombergian form but only ranges through Hartselle and Bangor equivalents, whereas *P. tulipaeformis* (=*P. brevis*), *P. robustus* (=*P. fohsi*, *P. chesterensis*, *P. hambachi*, and *P. hemisphericus*), and *P. speciosus* (=*P. clavatus* and *P. okawensis*) are restricted to upper Hombergian, Bangor–Glen Dean equivalents (Fig. 11.1). *P. laminatus* has only been reported from Elviran parts of the Pennington Formation in Alabama (Drahovzal, 1967) (Fig. 11.1).

Edrioasteroids are also known from Carboniferous rocks of the Appalachian Basin, but are generally rare to uncommon. The edrioasteroid *Hypsiclavus huntsvillae* is known only from Chesterian rocks of the Appalachian Basin, where it ranges from Genevievian to Hombergian (Chesnut and Ettensohn, 1988; Sumrall, 1996), and the edrioasteroid *Ulrichidiscus pulaskiensis* is known only from the upper Hombergian rocks of eastern Kentucky (Chesnut and Ettensohn, 1988).

Pennsylvanian Succession

Pennsylvanian rocks predominate at the surface in the Appalachian Basin and consist largely of fluvial or marginal-marine to terrestrial, coastal-plain, clastic sequences with former sources in the Alleghanian orogen. These generally fining-upward sequences are interrupted by cyclic, coarsening-upward, marine horizons related to glacial eustasy, and it is in these horizons that echinoderms occur as rare constituents of low-diversity faunas. The crinoid genera *Aatocrinus*, *Plaxocrinus*, *Delocrinus*, *Endelocrinus*, *Sciadocrinus*, *Metacromyocrinus*, *Diphuicrinus*, and *Paragassizocrinus* have been reported, and of these only *Paragassizocrinus*, *Endelocrinus*, and *Plaxocrinus* are known from more than one locality in the basin. The stemless *Paragassizocrinus* is an *Agassizocrinus* homeomorph, although unrelated to it. As currently known, *Paragassizocrinus tarri*, the most common species, ranges from late Morrowan to early Atokan (late Bashkirian–early Moscovian) time in the Appalachian Basin, although beyond the basin it probably ranges into Virgilian (late Kasimovian) time (Ettensohn, 1980). *Plaxocrinus* (=*Hydreionocrinus*) *mooresi*, on the other hand, ranges throughout the Pennsylvanian section (upper Morrowan–lower Virgilian; upper Bashkirian–upper Kasimovian) in Ohio and Kentucky parts of the Appalachian Basin (Morse, 1931; Ausich, 1996), whereas *Endelocrinus allegheniensis* is known only from the lower Virgilian Ames Limestone in Pennsylvania and West Virginia (Bassler and Moodey, 1943) (Fig. 11.1).

Conclusions

The Carboniferous was a period of major echinoderm evolution, especially during Mississippian time when crinoids, blastoids, and echinoids increased dramatically in abundance and diversity. Their high degree of structural organization and distinctive morphologies make them ideal zonal indicators, and during the Mississippian Period they provide greater biostratigraphic resolution than do conodonts and foraminifera. Echinoderms were especially abundant in the Middle and early Late Mississippian carbonate-rich seas, but already by Early Mississippian time they had made the shift to clastic-rich environments, which predominate in the Carboniferous rocks of the Appalachian Basin. Hence, echinoderms became very important in the early zonation of the Mississippian Period, a zonation that is still used today.

In general, well-preserved Kinderhookian, Osagean, and Meramecian echinoderm faunas are rare in the Appalachian Basin. In some cases, however, the occurrence of echinoderms, with reference to echinoderms in the Illinois Basin section, can aid in constraining the age of strata. Although late Kinderhookian and early Osagean faunas are present, most are endemic forms of little diagnostic value. By the middle and late Osagean, a number of diagnostic crinoids, mostly camerates living in clastic-rich environments, appear. The most diagnostic of these include *Aorocrinus, Abatocrinus, Actinocrinites, Alloprosallocrinus, Agaricocrinus, Azygocrinus, Dizgocrinus, Dorycrinus, Eretmocrinus, Eutrochocrinus, Macrocrinus,* and *Uperocrinus*. At the Osagean-Meramecian boundary, a major tectonic reorganization occurs across the east-central United States as a result of the Ouachita Orogeny, and clastic-rich environments are replaced by shallow-water carbonates. At the same time, most of the larger, many-plated camerate crinoids disappear, only to be replaced by cladids and smaller cladid-homeomorph camerates, while blastoids become more common. In the lower Meramecian Salem-Warsaw equivalents, for example, the small cladid-homeomorph camerate *Dichocrinus simplex* is diagnostic, and three blastoids, *Mesoblastus wortheni*, *Tricoelocrinus,* and *Pentremites conoideus*, attain their peak abundances. Another cladid-homeomorph camerate, *Platycrinites penicillus*, becomes especially diagnostic in upper Meramecian St. Louis equivalents and in lower Chesterian Ste. Genevieve equivalents, and the blastoid genus *Pentremites* becomes abundant for the first time as *P. puchellus* in Ste. Genevieve equivalents across the basin.

In lower Chesterian Gasperian parts of the section, another cladid-homeomorph camerate, *Talarocrinus,* replaces *P. penicillus* as the diagnostic form in the same facies, and there is brief, but major, evolutionary radiation of cladids, species of *Pentremites*, and species of another cladid-homeomorph camerate, *Pterotocrinus*. In particular, species of the cladid *Agassizocrinus*, of the blastoid *Pentremites*, and of the camerate *Pterotocrinus* provide relatively detailed zonation in lower and middle parts (Gasperian and Hombergian) of the Chesterian section. By late Chesterian (Elviran) time, an influx of marginal-marine and terrestrial clastics flooded the Appalachian Basin and continued through Pennsylvanian time. Rare echinoderms are present in these upper Chesterian and Pennsylvanian rocks and are sufficiently diagnostic to distinguish Mississippian and Pennsylvanian systems; however, these forms are too long-ranging to provide any smaller-scale zonation. Greater detail about the above Carboniferous echinoderm zonation is presented in a paper by Ettensohn and others (2007).

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12: Carboniferous Coral Succession In the Appalachian Basin

Frank R. Ettensohn and Walter K. Johnson

Introduction

Carboniferous rocks of the Appalachian Basin comprise a three-part lithologic succession, including Lower to Mid-Mississippian (Tournaisian–lower Viséan) clastics, Mid- to Upper Mississippian (upper Viséan) carbonates, and Upper Mississippian through Pennsylvanian (upper Viséan–Gzelian) clastics; corals, mostly Rugosa, are present locally in each part of the succession. Corals are relatively rare in clastic parts of the succession, and, even in the carbonates, are never very abundant. Where they do occur in carbonates, a few forms are commonly persistent at given horizons across great distances and have been used as biostratigraphic indicators. Nevertheless, Carboniferous corals in the Appalachian Basin are still poorly known, and only those in the carbonates have been examined in any detail, in large part because of perceived biostratigraphic significance.

Corals have played an important part in paleontological zonation of Carboniferous rocks in some parts of the world, but in North America they are generally inadequately known and their use for zonation has been minor. What use of corals has been made in North American Carboniferous rocks was pioneered by Stuart Weller (1926), but his zonation was based on the type Mississippian section in the Illinois Basin and was weighted heavily toward organism groups that were more abundant. As a result, corals were only used as zonal indicators in Meramecian (mid-Viséan) parts of the sequence where they are most abundant, and his *Lithostrotion canadense* Zone was the only zone based on corals. This zone has been recognized across much of the east-central United States, including parts of the Appalachian Basin, but the correlations have been regarded with some uncertainty beyond the Illinois Basin because they are not supported with biostratigraphic corroboration from other organism groups.

Overall, corals are not very common in Carboniferous rocks of the Appalachian Basin. Based on faunal lists (e.g., Bassler, 1950), diversity and abundances appear to be low, and where coralliferous facies are present, they exhibit moderate to high endemism (Sando and others, 1975). Patterns of endemism and diversity are most likely related to the isolated nature of the Appalachian Basin, which was an interior foreland basin during most of Carboniferous time. The basin was included in the Southeastern Zoogeographic Coral Province of Sando and others (1975) and was isolated by Acadian, Ouachita, or Alleghanian tectonic highlands on its southern and eastern margins and by the Cincinnati and Transcontinental Arches on its northern and western margins. Deeper waters and clastic-rich environments associated with these tectonic features were further isolating factors. In general, the clear, shallow-water, carbonate environments favored by most corals were not areally or temporally extensive in the Appalachian Basin because of the proximity and frequency of tectonic perturbations and the imposition of glacial-eustatic fluctuations. One interval for which Carboniferous coral zonation is especially effective across the Appalachian and adjacent basins, however, reflects a widespread, Meramecian area of shallow-water, carbonate deposition that paralleled the Ouachita orogen and may represent Ouachita bulge uplift into shallow, agitated waters (Ettensohn, 1993), conducive to both carbonate production and proliferation of corals.

Although several genera and species have been recorded from both clastic and carbonate parts of the Appalachian Carboniferous section, we have noted as diagnostic below and in Figure 12.1 only those forms that are clearly identified and appear to be relatively common across large parts of the basin. Because there has been little major work on corals in the area since the 1950's, this report is essentially a survey based on earlier faunal studies.

Mississippian Succession

Kinderhookian

Kinderhookian (lower Tournaisian) rocks in the Appalachian Basin consist largely of basinal, black or dark gray shales in Sunbury or Chattanooga formations, deposited in deeper, anoxic to dysoxic conditions. Locally, these conditions persisted into Osagean time, but wherever they occur, faunas of any sort are extremely rare. On the eastern margins of the basin, the dark shales intertongue with coarser, marginal-marine to terrestrial clastics in which faunas are relatively uncommon. Hence, to the best of our knowledge, corals have not been reported from Kinderhookian rocks in the Appalachian Basin.

Osagean

Osagean (upper Tournaisian–lower Viséan) rocks in the Appalachian Basin largely consist of post-Acadian, deltaic shales, mudstones, siltstones, and sandstones deposited in basinal, prodelta, and delta-front environments represented by the Borden, Grainger, and Price Formations. The tabulate corals *Favosites*, *Cladochonus,* and *Palaeacis*, as well as the rugosans *Cyathaxonia*, *Trochophyllum*, *Amplexus*, *Zaphrentoides,* and *Baryphyllum*, have been reported from the above units and their Fort Payne equivalents. After late Osagean delta abandonment, deeper-water, cherty carbonates and carbonate-

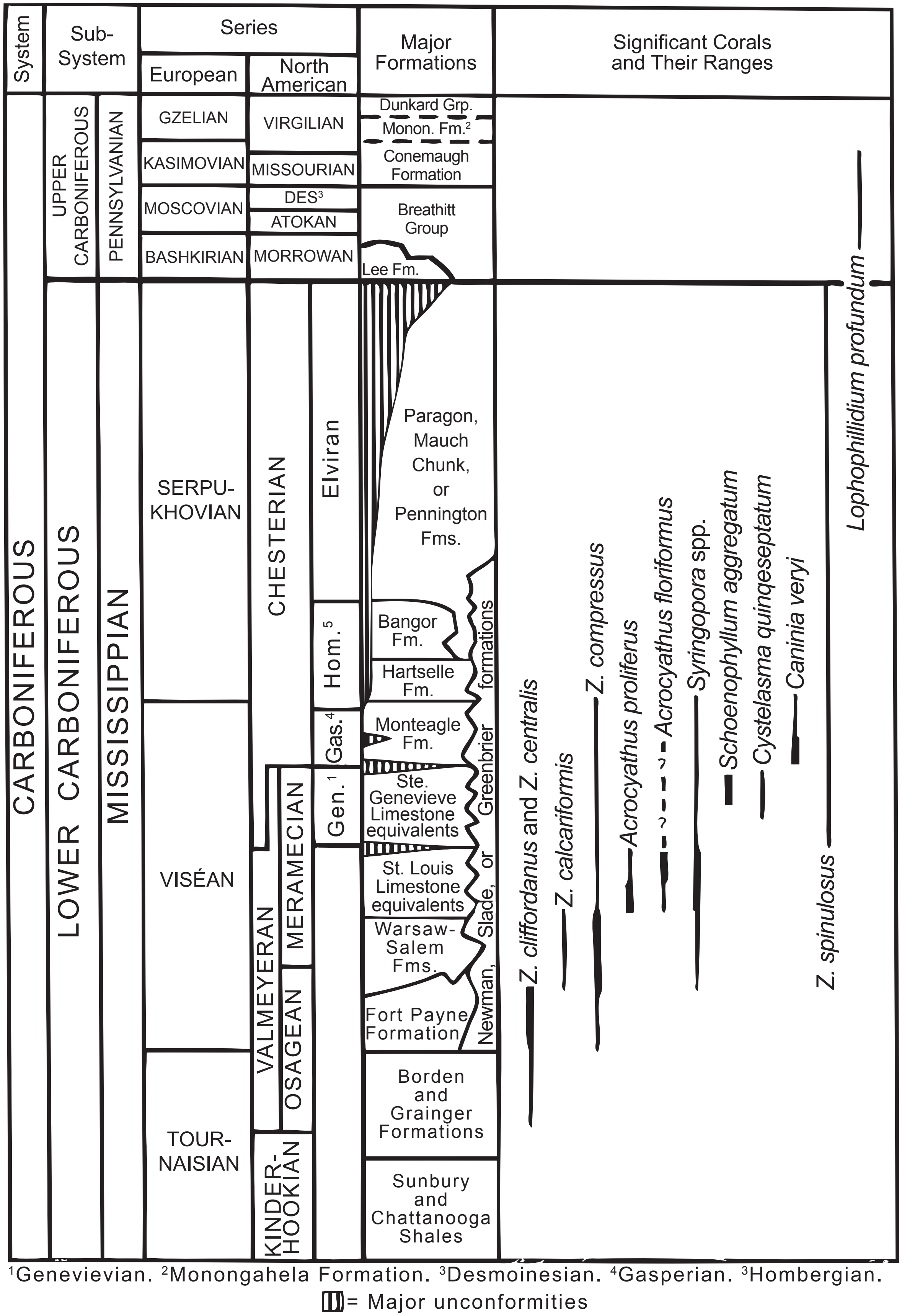

Figure 12.1. Stratigraphic distribution of diagnostic Carboniferous corals in the Appalachian Basin. The representation of stages is not necessarily proportional to the time they represent.

rich clastics of the Fort Payne Formation infilled the basin seaward of the abandoned delta front, so that the Fort Payne Formation predominates in this interval throughout southern and southwestern parts of the Appalachian Basin. Carbonate buildups or mud mounds are locally common in the Fort Payne, and some of the coral genera noted above commonly comprise parts of mud-mound faunas. Of the above genera, however, only species of *Zaphrentoides*, *Z. cliffordanus,* and *Z. centralis* are sufficiently widespread to have diagnostic value. Although these two species have been found in underlying deltaic clastics, they apparently do not occur above the Fort Payne and its equivalents and, therefore, probably indicate an Osagean age (Fig. 12.1). Nonetheless, in the literature these species are used with several different genus designations, including *Zaphrentis*, *Triplophyllites*, *Triplophyllum,* and *Amplexizaphrentis*, that, according to Easton (1975), all are synonymous with *Zaphrentoides.*

Meramecian

By Meramecian (mid-Viséan) time, the Appalachian foreland basin was filled with post-Acadian deltaic clastics or deeper-water Fort Payne carbonates and clastics, and a transition to shallow-water, carbonate deposition was ongoing. The widespread nature of this transition, paralleling the southern flank of the continent in the east-central and central United States, suggests that it may have been related to regional uplift accompanying early Ouachita bulge moveout (Ettensohn, 1993). In the Appalachian Basin, the transition occurs in the Warsaw-Salem interval, which may have equivalents in upper parts of the Borden Formation or in lower parts of the Slade, Newman, or Greenbrier limestones. The interval is commonly dolomitic and shaly, and corals in the genera *Zaphrentoides*, *Amplexus,* and *Cladochonus* have been reported. Though relatively uncommon, only one species in the genus *Zaphrentoides*, *Z. calcariformis*, is sufficiently widespread to be diagnostic of this lower Meramecian interval (Fig. 12.1). Although *Z. compressus* is also common in this interval, in the Appalachian Basin it has a longer range in upper Osagean through lower Chesterian rocks (Fig. 12.1). Both of these *Zaphrentoides* species have been associated with various genus names, including *Zaphrentis*, *Triplophyllum*, *Triplophyllites,* and *Hapsiphyllum*, but according to Easton (1975), *Zaphrentoides* is the senior synonym.

The St. Louis Formation and its equivalents (e.g., Hillsdale and Tuscumbia formations) in the Appalachian Basin are among the most widespread and distinctive Meramecian units in the central United States, and they contain the same distinctive, low-diversity coral fauna nearly everywhere. Equivalents in the Appalachian Basin represent transgressive, shallow, open-marine, carbonate environments, and the most abundant corals generally occur in basal calcarenitic parts of the unit from Kentucky and West Virginia southward to Georgia and Alabama. The fauna generally includes three species, *Acrocyathus floriformis*, *Acrocyathus proliferus,* and *Syringopora virginica* (Fig. 12.1). Species of *Syringopora* are quite common in the St. Louis, but in parts of the Appalachian Basin they range both above and below St. Louis equivalents. *A. floriformis* colonies have characteristic polygonal corallites and are reported in most of the available literature as synonymous species of the genera *Lithostrotion* or *Lithostrotionella*, including *L. canadense*(*is*), *L. hemispericum*(*a*), *L. americanum*(*a*), *L. basaltiforme*(*is*), and *L. castelnaui* (Sando, 1983). This species is known only from the St. Louis and its equivalents, with the single exception of a report from the lower Chestererian (Gasperian) rocks of Georgia (Butts, 1948). *A. proliferus* colonies, on the other hand, have round corallites and are typically reported as the junior synonyms, *Lithostrotion proliferum* or *Lithostrotionella prolifera*. Although both species have been reported throughout the St. Louis and its equivalents, *A. proliferus* is generally more common in lower parts and *A. floriformis* in upper parts of the unit (Butts, 1922; Easton, 1943). It is possible, however, that *A. proliferus* and *A. floriformis* are merely ecologic variants of each other (Sando, 1983).

Chesterian

The Ste. Genevieve Formation and its equivalents (e.g., Denmar and lower Monteagle formations) in the Appalachian Basin represent very shallow-water, commonly oolitic environments that reflect the culmination of Meramecian uplift and shallowing across the southern flank of the continent. These units are now frequently included in the Chesterian Stage (mid-Viséan–Serpukhovian) (Maples and Waters, 1987), but for most of their histories have resided in the Meramecian Stage. Corals in the genera *Syringopora*, *Cystelasma*, *Michelinia*, *Zaphrentoides,* and *Schoenophyllum* have been reported from Ste. Genevieve equivalents in the Appalachian Basin. *Zaphrentoides spinulosus*, also known under the genus names *Zaphrentis*, *Triplophyllum*, *Hapsiphyllum*, *Menophyllum,* or *Triplophyllites* (see Easton, 1975), first occurs in Ste. Genevieve equivalents of the Appalachian Basin, although it is present much earlier in mid-Osagean Fort Payne equivalents in the Illinois Basin. Unfortunately, the species is not very diagnostic in the Appalachian Basin, for it ranges from Ste. Genevieve equivalents throughout the entire Chesterian (Easton, 1943) (Fig. 12.1). *Schoenophyllum aggregatum*, also known by the junior synonyms *Lithostrotion harmodites* or *Siphonodendron genevievensis* (see Easton, 1957), is a very common Ste. Genevieve indicator throughout the Illinois Basin and adjacent areas, but in the Appalachian Basin is reported only from equivalents in south-central Kentucky and adjacent parts of Tennessee. *Cystelasma quinqueseptatum*, however, is more widespread, occurring in Alabama, Tennessee, Virginia, and Georgia, making it the most diagnostic Ste. Genevieve coral in the Appalachian Basin (Fig. 12.1).

Overlying lower Chesterian (Gasperian) rocks in the Appalachian Basin are largely high-energy, oolitic, and bioclastic calcarenites and are characterized by a few species of *Amplexus*, *Michelinia*, *Syringopora*, the ubiquitous *Z. spinulosus,* and *Caninia veryi*. *C. veryi*, also known as *Lithodrumus veryi* and *Campophyllum gasperense* (Easton, 1943), is especially diagnostic of the interval. *C. veryi* apparently preferred the more open-marine, central parts of the Appalachian Basin, for it is unknown from more restrictive, very shallow-water and peritidal environments that occurred on the margins of the basin in areas such as northeastern Kentucky. Carbonates in middle (Hombergian) and upper (Elviran) Chesterian parts of the section become increasingly argillaceous, and clastic intervals increase in abundance. *Z. spinulosus* is the only common coral.

Pennsylvanian Succession

Pennsylvanian rocks predominate at the surface in the Appalachian Basin and consist largely of fluvial or marginal-marine to terrestrial, coastal-plain, clastic sequences with former sources in the Alleghanian orogen. These generally fining-upward sequences are interrupted by cyclic, coarsening-upward marine horizons related to glacial eustasy, and it is in these horizons that corals occur as rare constituents of low-diversity faunas. The genera C*ladochonus*, *Chaetetes,* and *Lophophyllidium* have been reported. *Lopophyllidium profundum*, also known under the genus names *Cyathaxonia* and *Lophophyllum*, is probably the most abundant and widespread of these corals, ranging from late Morrowan to early Virgilian (late Bashkirian–late Kosimovian) time in the Appalachian Basin (Fig. 12.1).

Conclusions

During Carboniferous time, the Appalachian Basin was an isolated, internal foreland basin coeval with parts of three orogenies, and most environments were discontinuous and ephemeral because of tectonic and eustatic perturbations. Consequently, coral faunas are not very common, and where they do occur, they exhibit low diversity and moderate to high endemism. The use of corals for Carboniferous zonation in North America began in the Illinois Basin, and hence, most Appalachian Basin correlations are presented relative to Illinois Basin series, stage, or formation equivalents, even though the ranges of some corals appear to differ from basin to basin. Nonetheless, as currently known, eight species with diagnostic value are present in Osagean, Meramecian, and lower Chesterian rocks of the Appalachian Basin. Of these, Meramecian corals in St. Louis and Ste. Genevieve equivalents provide the best correlations between rocks in the Appalachian Basin and coeval rocks elsewhere along the southern flank of the continent because of the unusual continuity of carbonate environments at the time. The few corals in middle and upper Chesterian and Pennsylvanian rocks, where present, are sufficiently diagnostic to distinguish Mississippian and Pennsylvanian Systems; however, these forms are too long-ranging to provide any smaller-scale zonation.

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13: Ostracodes as a Tool for Understanding Environmental Distribution in the Carboniferous Strata of the Eastern United States

Christopher Dewey

Introduction

Carboniferous ostracodes are very common in the Illinois, Appalachian, and Black Warrior Basins and may be found in lithologies ranging from dense limestones to fine-grained shales. Ostracodes possess great potential as markers for both time and environment because of their abundance and widespread occurrence in a variety of lithologies representing most environments from freshwater through deep basinal conditions. It is unfortunate, however, that the application of ostracodes to both biostratigraphic and paleoenvironmental problem-solving has been hindered by the taxonomic redundancies that developed in the early years of study between the late 1800's and early 1940's. The taxonomic problems, which exist at the species and genus levels, have thus far precluded the possibility of creating a viable, detailed ostracode biozonation for the Carboniferous, but by using the morphological characteristics available at higher taxonomic levels it has been possible to develop a reliable paleoenvironmental tool.

Since the paleoenvironmental tool operates at a high taxonomic level, it may have a broad applicability to any Carboniferous, freshwater through shallow marine (shoreline to shelf edge) ostracode fauna. The model is of particular importance in the depositional basins of the eastern United States because transgressive-regressive cyclicity led to the deposition of fine-grained clastic sediments, which may appear lithologically similar, but were widely deposited in radically different depositional environments. The paleoenvironmental diagram (Fig. 13.1) has evolved over several years and employs data from several studies, summarized in Dewey and Puckett (1993).

History of Study

The foundation for the study of Carboniferous ostracodes in North America was provided by Ulrich (1891). The major taxonomic base was created from a series of studies in the Midcontinental region by Cooper, Coryell, and his students and Croneis and his students; typical examples include Coryell (1928), Coryell and Sohn (1938), Croneis and Bristol (1939), Croneis and Thurman (1939), Coryell and Johnson (1939), and Cooper (1941, 1946). These papers represent a very small sampling of the work that was done during the 1930's and 1940's, work, which although describing many of the currently recognized taxa, was the basis of much of the taxonomic confusion at the species level today. Unfortunately, very few workers have been willing to tackle the taxonomic issues, with the notable exception of Sohn (1960, 1961, 1988).

Depositional and Paleoenvironmental Setting

As a gross simplification, the Lower Carboniferous strata of the Illinois, Appalachian, and Black Warrior Basins can be interpreted as a series of sand-shale-limestone cyclothems, which represent the results of an interplay between the transgressive-regressive cycles of the Kaskaskia and the erosion of nearby orogenic highlands. Depositional environments include a carbonate shelf sequence, which intertongues with progradational clastic units of deltaic, other shoreline, and freshwater environments. In the Upper Carboniferous, cyclothemic deposition continued during the Absaroka, but was modified by the glacial-eustatic effects of the Gondwanan glaciation. Idealized, coal-bearing Upper Carboniferous cyclothems of the eastern United States contain a lower, regressive or progradational freshwater part and an upper, transgressive marine part.

It is important to recognize that the two main controls upon the distribution of ostracodes in cyclothemic deposits were therefore (1) the interaction of siliciclastic sediment-laden fresh water from terrestrial runoff with open-marine, carbonate-producing, normal-marine-salinity waters on the craton and (2) the modifying effects of regional climate patterns. Lithostratigraphically, this can be related to the extent of freshwater facies together with the interaction of clastic progradational events onto an open shelf associated with carbonate-producing transgressive events in both humid and semiarid climates. Consequently, the distribution of particular groups of ostracodes was not simply a function of proximity to shore per se, but rather the extent to which progradational and/or climatic events were effective in altering biofacies distributions. As an example, an area adjacent to a prograding delta in a humid climate might have been subjected to an influx of fine clastic sediment and an associated reduction in paleosalinity caused by freshwater runoff. Conversely, an area away from any site of progradational activity may have been a carbonate-producing environment subject to normal marine salinities. In both examples the environments might have been equidistant from shoreline. In this manner it is possible to bring the sedimentologic and micropaleontologic data into conformity with one another because the micropaleontologic data provide evidence

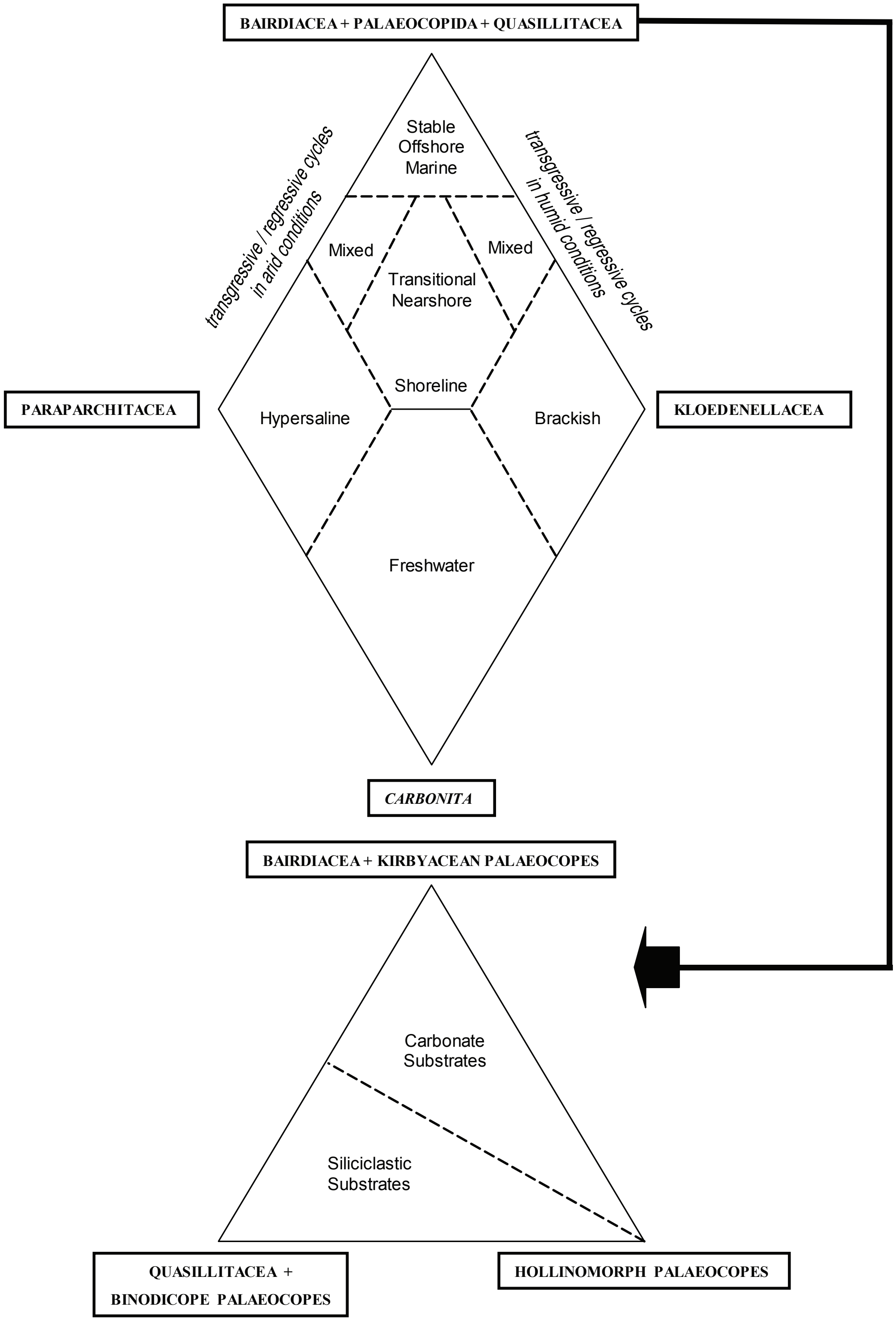

Figure 13.1. Paleoenvironmental diagram of major Carboniferous ostracode groups.

of paleoenvironmental fluctuations that are not readily visible in the sediments alone.

Ostracode Assemblages

Four main and three subset assemblages can be recognized in freshwater, shoreline, and shallow marine ostracode faunas of the eastern United States:

1. A bairdiacean-palaeocope-quasillitacean assemblage that is found in a variety of substrates in shallow subtidal, normal marine salinity conditions. This assemblage can be further refined as follows:

A. A quasillitacean-amphissitid-binodicope assemblage occurring in fine clastic substrates.
B. A bairdiacean-kirkbyacean assemblage occurring in carbonate substrates.
C. A hollinomorph assemblage where mixed or rapidly alternating substrates were common.

2. A kloedenellacean assemblage that occurs in fine clastic substrates in "near-shore" conditions, where lowered salinities may have been a controlling factor.
3. A paraparchitacean assemblage that occurs in near-shore environments where raised salinities may have been a controlling factor.
4. A *Carbonita* assemblage associated with freshwater conditions.

The assemblage model (Fig. 13.1) incorporates qualitative results from studies of the Illinois Basin (e.g., Cooper, 1941) and quantitative results from the Lower Carboniferous sediments of the Maritimes Basin of Canada and the Black Warrior Basin of Alabama (Dewey, 1989; Dewey and Puckett, 1993), as well as the *Carbonita* faunas of the United States and Canada (Swain, 1999; Tibert and Dewey, 2006). The diagram was constructed by selecting environmentally sensitive taxa at the suprafamilial level or higher, recalculating their totals to 100 percent (omitting all members of higher taxa not included), and plotting the relative percentages in the ternary space. The current model allows for the occurrence of "mixed" assemblages such as a mixed bairdiacean-glyptopleurid assemblage, which has been found in fine clastic shallow-marine conditions close to a shoreline setting. In this instance, the presence of typically marine bairdiaceans together with the glyptopleurid kloedenellaceans (and a scarcity of geisinid kloedenellaceans) indicate "mixed."

Discussion

The strength of using ternary diagrams based upon taxa of relatively high rank is that the model acknowledges that not all species within a given taxon must occur within a single paleoenvironment. It does, however, recognize that in some cases the majority of species of a taxon can tend to exhibit similar paleoenvironmental tolerances. Consequently, there are some high-order taxa whose species members are always associated with particular types of environments and other high-order taxa whose species members are found across a broad range of environmental conditions. The development of the model draws upon several well-established characteristics of Carboniferous ostracode faunas. It is recognized that kloedenellacean ostracodes were common in near-shore conditions, that the Paraparchitacea were tolerant of normal-marine through hypersaline conditions, that the Bairdiacea were indicative of normal-marine offshore conditions, and that *Carbonita* is typically found in freshwater environments.

Recently, independent isotopic evidence from the Early Carboniferous of Scotland (Williams and others, 2005) gave support for the model, as did a detailed taxonomic investigation of a traditional "*Carbonita*" fauna from Nova Scotia (Tibert and Dewey, 2006).

One of the major strengths of this type of model is that the plot can be employed without an intricate knowledge of alpha taxonomy, provided that any species-level taxon can be assigned to the correct higher taxon. By implication, a nonspecialist can use the ternary diagram with only knowledge of the morphological criteria necessary to define the higher taxa of Carboniferous ostracodes.

By dealing with relative percentages and not absolute numbers of individuals, it is possible to have faunas with dissimilar absolute abundance of taxa yield erroneous results. Clearly, the larger the number of individuals analyzed, the more robust will be the results. By using randomly picked statistical populations in excess of 300 individuals, however, problems of this nature can be minimized. Despite the statistical limitation, ternary diagrams have been used with great success for benthic foraminiferids (Murray, 1991) and can be used in a similar way for Carboniferous ostracodes.

Although ostracode faunas are susceptible to the effects of post-mortem transport prior to burial, sedimentary reworking, dissolution diagenesis, and poor collecting procedures, careful attention to evidence of abrasion, grain-size sorting, and selective preservation, combined with precise collecting protocols, can minimize these sources of error.

Closing Comment

Sohn and Jones (1984) presented a preliminary global biostratigraphic zonation as a "subjective evaluation of only a few of the more promising taxa for correlation." Their discussion also enumerated many of the problems inherent in biostratigraphic work with ostracodes. Although no biostratigraphic zonations have been presented herein, the species richness of Carboniferous ostracode faunas indicates that their biostratigraphic utility would be very high if current taxonomic problems could be surmounted. Morphometric analysis combined with archival investigations of the type materials would help to reduce the taxonomic duplication, which currently obscures the true stratigraphic ranges of potentially useful ostracode taxa. It is perhaps encouraging to note that the morphologically distinct species *Amphissites insignis* has been shown to be a Late Mississippian marker in the United States (Sohn, 1986) and also tested as such by Dewey (1992). More such individual studies supported by robust and accurate taxonomy are needed.

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On the Front Cover:

1. Pennsylvanian and Mississippian strata at Pound Gap, Ky.
2. Pennsylvanian ammonoid *Diabloceras neumeieri* Quinn and Carr (from Work and others, this volume)
3. Mississippian ammonoid, *Kazakhstania mangeri* Work and Mason (from Work and others, this volume)
4. *Agassizocrinus,* a Mississippian index fossil (photo courtesy of Frank Ettensohn)
5. *Lycospora pellucida* , a Lower Pennsylvanian index spore (photo courtesy of Cortland Eble)
6. *Schulzospora campyloptera,* an Upper Mississippian index spore (photo courtesy of Cortland Eble)