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NO MAJOR STRATIGRAPHIC GAP EXISTS NEAR THE MIDDLE–UPPER PENNSYLVANIAN (DESMOINESIAN–MISSOURIAN) BOUNDARY IN NORTH AMERICA

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ABSTRACT

Interregional correlation of the marine zones of major cyclothems between North America and eastern Europe does not support assertions that a major stratigraphic gap exists between the traditional regional Desmoinesian and Missourian stages in North America. Such a gap was previously proposed to explain an abrupt change in megafloral assemblages in the northern Appalachian Basin and by extension across all of North America. Conodont-based correlation from the essentially complete low-shelf Midcontinent succession (distal from the highstand shoreline), through the mid-shelf Illinois Basin, to the high shelf of the Appalachian Basin (proximal to highstand shoreline) demonstrates that all major ~400 kyr cyclothem groupings in the Midcontinent are recognizable in the Illinois Basin. In the Appalachian Basin, however, the grouping at the base of the Missourian is represented only by paleosols and localized coal. The immediately preceding grouping was removed very locally by paleovalley incision, as is evident at the 7–11 Mine, Columbiana County, Ohio, from which the original megafloral data were derived. At the few localities where incised paleodrainage exists, there may be a gap of ~1000 kyr, but a gap of no more than ~600 kyr occurs elsewhere in the Appalachian Basin at that level and its magnitude progressively decreases westward into the Illinois (~300 kyr) and Midcontinent (<200 kyr) Basins. Thus, while a gap is present near the Desmoinesian–Missourian boundary in North America, it is typically more than an order of magnitude smaller than that originally proposed and is similar to the gaps inferred at sequence boundaries between cyclothems at many horizons in the Pennsylvanian of North America.

INTRODUCTION

Wagner and Lyons (1997) proposed that a major unconformity was present at the Desmoinesian–Missourian (Middle–Upper Pennsylvanian) boundary in the northern Appalachian Basin of the United States. Their reasoning was based in part on the extension to North America of a system of megafloral biozonation developed in western Europe, particularly in a series of small basins in northern Spain (e.g., Wagner, 1984; Cleal, 2007). This biozonation relies on plant fossils because marine index fossils are largely absent in the dominantly terrestrial successions of western Europe (Fig. 1; Heckel and Clayton, 2006). Under this system (Wagner and Lyons, 1997), the Appalachian Basin lacks megafloral remains typifying most of the Stephanian Stage (formerly Series) of western Europe (=Kasimovian–lower Gzhelian). Specifically, they suggested that most of the Cantabrian Substage (which straddles the Desmoinesian–Missourian boundary), all of Stephanian Substage A (Barruelian), Substage B, and much, if not all, of Substage C are absent in the Appalachian Basin and, as asserted later, throughout North America (Wagner, 2003; Wagner and Álvarez-Vázquez, 2010). Wagner and Lyons (1997) positioned their unconformity within the lowermost Conemaugh Group of the Appalachian Basin. Based on megafloral assemblages, they indicated that the roof shales of the Upper Freeport coal are of basal Stephanian (early Cantabrian) age, while the remainder of the Conemaugh Group is late Stephanian C or even early Autunian in age, similar to the lower Rotliegend of western Europe.

Wagner and Lyons (1997) further suggested that this gap was also present in some smaller basins in eastern North America, including the Sydney Basin of Maritime Canada. The only basin in eastern North America in which these authors noted megafloral assemblages that possibly represented the Stephanian A (Barruelian) or B, was the Narragansett Basin of Rhode Island and eastern Massachusetts. Wagner (2003) later proposed that the gap was also present in the Illinois and Midcontinent basins, based on the abrupt transition between Desmoinesian and Missourian floras, which was reported and analyzed in numerous publications (Phillips et al., 1974, 1985; Pfefferkorn and Thomson, 1982; Kosanke and Cecil, 1996; DiMichele and Phillips, 1996; Peppers, 1996; Blake et al., 2002; Pfefferkorn et al., 2008; DiMichele et al., 2009). Thus, the far-reaching hypothesis put forward was that a major stratigraphic gap occurred at the Desmoinesian–Missourian boundary over most of eastern and central North America, as is the case across much of northwest Europe (Cleal, 2007).

Over the past decade Wagner and Lyons' (1997) hypothesis has strongly influenced the understanding of some leading biostratigraphers (Cleal et al., 2003; C.J. Cleal, personal communication, 2009) and is often cited. For example, Dimitrova et al. (2009, fig. 2) show the proposed gap in North America on their interregional correlation chart. Nonetheless, the hypothesis has not been universally accepted and indeed has been the subject of critical analysis (Blake et al., 2002). The aim of this current paper is to test Wagner and Lyons' (1997) hypothesis using independent age constraints derived from new interregional correlations of the bracketing marine zones, based principally on conodont faunas, between the Midcontinent Basin of North America and the Donets and Moscow basins of eastern Europe. This critical analysis of Wagner and Lyons' (1997) principal datasets shows that no significant stratigraphic gap exists near the Desmoinesian–Missourian boundary in North America, and thus falsifies the scale of the gap asserted in their hypothesis.

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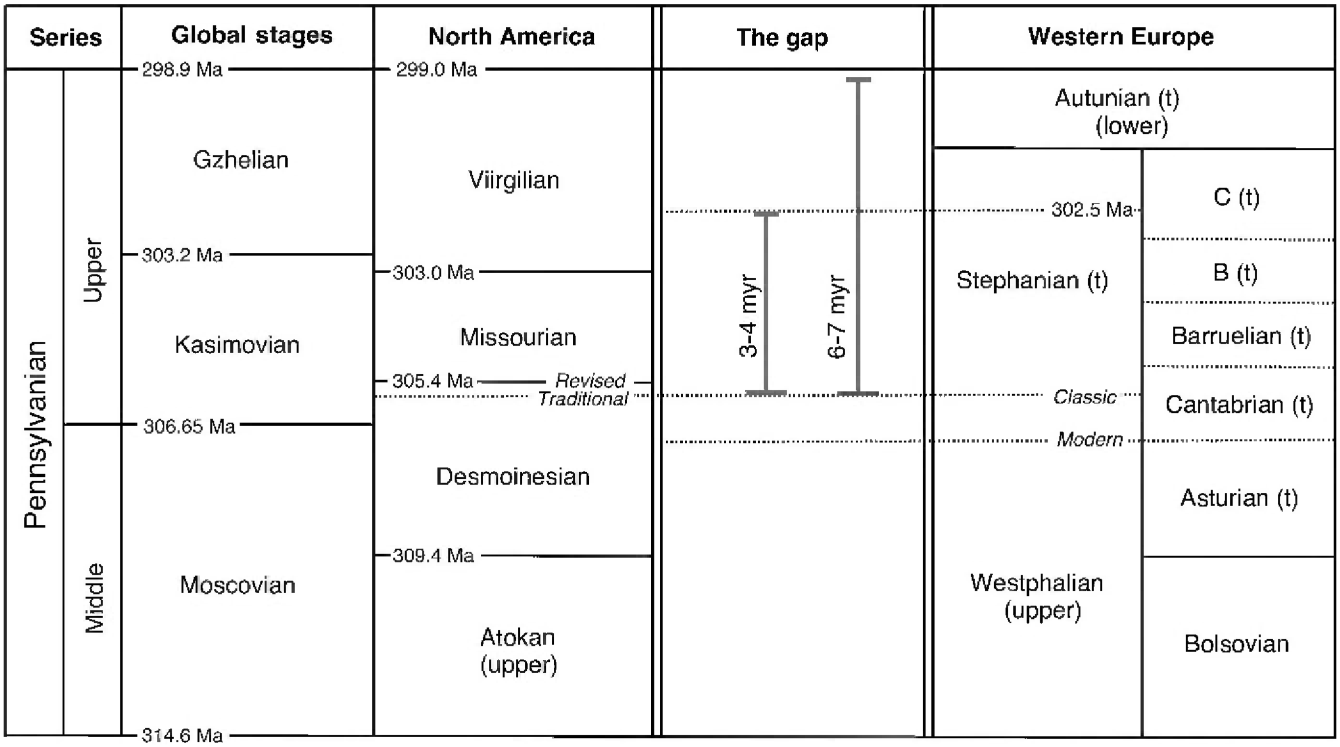

FIGURE 1—Correlation of Pennsylvanian global stages in eastern Europe with North American and western European regional stages (Table 1; modified from Heckel and Clayton, 2006, fig. 2; Heckel et al., 2007), illustrating two possible magnitudes for the gap. Boundary dates in North America are based on cyclothem calibration of Heckel (2008), and those for global stages on Davydov et al. (2010). Radiometric date in western Europe column is from mid-Stephanian C tonstein from Breitenbach Formation in Saar-Lorraine Basin (Burger et al., 1997, recalibrated by Gradstein et al., 2004); t = mainly terrestrial succession.

WAGNER AND LYONS' GAP

In this paper, the term the gap is employed to refer to Wagner and Lyons' (1997) proposed major stratigraphic gap and to distinguish their concept from the other smaller stratigraphic gaps that are discussed.

Nomenclature of Key Stratigraphic Boundaries

In North American basins there are three chronostratigraphic boundaries defined by different criteria that fall within the crucial interval of the gap, none of which are identical, but all closely positioned (Fig. 1). The definitions of some of these boundaries have changed in recent times as follows:

Desmoinesian–Missourian Stage Boundary of North America.—The traditional boundary coincided with what is called the major floral step change, which is well documented (DiMichele et al., 2009; Falcon-Lang and DiMichele, 2010). This change occurs between the Mahoning and Mason coals in the Appalachian Basin, the Pond Creek and Lake Creek coals in the southern Illinois Basin, the Rock Branch and Athensville coals in the western Illinois Basin, and the Dawson and Tulsa-Hepler coals in the Midcontinent. This step change is characterized by the abrupt disappearance of *Lycospora*-producing lycopsids and many other taxa (Phillips et al., 1974; DiMichele and Phillips, 1996; Kosanke and Cecil, 1996; Peppers, 1996). The revised Desmoinesian–Missourian boundary occurs at slightly higher stratigraphic level defined by the first appearance of the conodont *Idiognathodus eccentricus* in the Exline Limestone in the Midcontinent Basin (Heckel et al., 2002). This is just below the Exline-equivalent Scottville Limestone but above the Athensville Coal in the Illinois Basin, and, like the traditional boundary, lies within the gap between the Mahoning and Mason coals in the Appalachian Basin. It should be noted that the lithostratigraphic Allegheny-Conemaugh Group boundary (which is used for mapping purposes in the Appalachian Basin) has remained at its traditional position at the top of the Upper Freeport coal.

Moscovian–Kasimovian Stage Boundary of the Eastern European Region.—This marine-based boundary involves the global stage names, but has not yet been officially designated. Based on conodonts in marine zones, the currently used Moscovian–Kasimovian Stage boundary is correlative within the upper Desmoinesian, somewhat below both the traditional and revised Desmoinesian–Missourian boundaries in North America (Fig. 1; Table 1).

Westphalian–Stephanian Stage Boundary of the Western European Region.—The classic boundary, defined in dominantly terrestrial successions, was positioned at a level correlative with the major floral step change at the traditional Desmoinesian–Missourian boundary. The modern boundary, however, coincides with the base of the Cantabrian (Wagner and Winkler Prins, 1985) and was placed using megafloras at different lower levels in different North American basins, e.g., just above the Upper Freeport coal in the Appalachians (Wagner and Lyons, 1997), but just above the significantly older Colchester coal in the Illinois Basin (Cleal et al., 2003), which is equivalent to the Lower Kittanning coal in the Appalachians and several coals below the Upper Freeport (Peppers, 1996). The rare conodont faunas of the type Cantabrian of northern Spain have not yet been systematically studied (T.I. Nemyrovska, personal communication, 2010), but one that contains morphotypes that resemble *I. delicatus* may be late Myachkovian (T.I. Nemyrovska and A.S. Alekseev, personal communications, 2010), i.e., latest Moscovian, just below the current base of the Kasimovian (Table 1). Therefore, the modern Westphalian-Stephanian boundary cannot, at present, be precisely correlated with other regions and is shown as dashed lines on the interregional correlation chart (Fig. 1; Heckel and Clayton, 2006). Based on megafloras, it likely falls within the upper Desmoinesian.

Uncertain Placement of the Gap in the Appalachian Basin

Wagner and Lyons (1997) placed the gap above the roof shales of the Upper Freeport coal within the lowermost part of the Conemaugh

TABLE 1—Correlation of major marine and some lesser cyclothems between Midcontinent Basin of North America, Moscow Basin of Russia (cratonic basin like the Midcontinent), and Donets Basin of Ukraine (rapidly subsiding aulacogenic basin), based on genera and species of conodonts (modified from Heckel et al., 2007); only taxa useful for correlation are shown. Core shale = conodont-rich shale, which also occurs in some intermediate cyclothems. Bold brackets enclose critical Appalachian equivalents of Midcontinent units. Note that Donets Basin stratigraphic terminology uses Roman letters followed by numbers of decreasing scale, separated by a dash for each marine unit in this table. Disappearance of *Lycospora*-producing lycopsids at level of limestone N_4 in Donets Basin was not specified as above or below (Teteryuk, 1974). FAD = First Appearance Datum of specific conodont taxa; LAD = Last Appearance Datum; (type) = type region for conodont taxon.

Global Stages		**NORTH AMERICAN MIDCONTINENT cyclothems [OK-KS-MO-IA] [MAJOR (core shale), Intermediate,** Minor**]**	**MOSCOW BASIN Afanasievo Quarry + Moscow cores [MAJOR CYCLE;** Lesser cycle**]**	**DONETS BASIN mostly Kalinovo section [MAJOR CYCLE;** Lesser cycle**]**
Gzhelian	**Virgilian**	**OREAD (Heebner)** FAD *Idiognathodus simulator* (type); *I. tersus*	**UPPER RUSAVKINO** FAD *Idiognathodus simulator; I.tersus*	**O6** FAD *Idiognathodus simulator*
Kasimovian		**CASS (Little Pawnee)** FAD *Streptognathodus zethus*	**MIDDLE RUSAVKINO** FAD *Streptognathodus zethus*	**O5** FAD *Streptognathodus zethus*
	Missourian	**Iatan**	Lower Rusavkino	(not identified)
		South Bend (Gretna)	Basal Rusavkino	(not identified)
		STANTON (Eudora) FAD *Idiognathodus eudoraensis* (type)	**TROSHKOVO** FAD *Idiognathodus eudoraensis*	**O4-6**
		Plattsburg (Hickory Creek)	Myasnitskaya	O4-5
		Wyandotte (Quindaro)	Sadovaya	O4-4
		IOLA (Muncie Creek)	Presnya	**O4-3**
		DEWEY (Quivira)	**MESTSHERINO**	**O4-1**
		Cherryvale (Wea)	Perkhurovo	O4
		Hogshooter	(not identified)	O3
		DENNIS (Stark) [= Pine Creek, Upper Brush Creek Ls] *Idiognathodus confragus* (type)	**UPPER NEVEROVO**	**O2** *Idiognathodus* cf. *confragus*
		Mound Valley FAD *Idiognathodus confragus*	(not identified)	O1-2 *Idiognathodus* cf. *confragus*
		SWOPE (Hushpuckney) [= Brush Creek Ls & Coal] FAD *Idiognathodus cancellosus* (type), type *I. sulciferus*	**MID-NEVEROVO** *I.* cf. *cancellosus, I.* cf. *sulciferus*	**O1** *Idiognathodus* cf. *sulciferus*
		HERTHA (Mound City) [highest likely position of New Galilee and 'Mason' coals]	Lower Neverovo	**N5-1**
		Exline FAD *Idiognathodus eccentricus*	Basal Neverovo *Idiognathodus* cf. *eccentricus*	N5
	Desmoinesian	Checkerboard-S. Mound, including Tulsa & Hepler coals	(not identified)	(not identified)
		Position of 'Major floral step change': loss of arborescent lycopsids		
		Glenpool = upper Lost Branch LAD *Neognathodus* sp.	Ratmirovo	N4 LAD *Neognathodus* sp.
		LOST BRANCH (Nuyaka Creek) including Dawson Coal *Swadelina nodocarinata* (type) **[= Mahoning Coal]**	**VOSKRESENSK** *Swadelina nodocarinata*	**N3-3** *Swadelina nodocarinata*
		Norfleet	Upper Suvorovo	N3-2
		ALTAMONT (Lake Neosho) [= Upper Freeport Coal] type *Swadelina neoshoensis*	**MID-SUVOROVO** type *Streptognathodus subexcelsus*	**N3-1**
		Farlington, including Mulberry Coal FAD *Swadelina neoshoensis*	Lower Suvorovo FAD *Streptognathodus subexcelsus*	N3 FAD *S. subexcelsus,* *S. neoshoensis*
Moscovian		**Coal City (Joe)** *Idiognathodus delicatus* (type)	Upper Peski *Idiognathodus delicatus*	N2-1
		PAWNEE (Anna) *Idiognathodus delicatus*	Middle Peski *Idiognathodus delicatus*	**N2** *Idiognathodus* cf. *delicatus*

Group in the Appalachian Basin, based on an inferred megafloral break (a change in megafloras) at this level. Later, Wagner (2003) equated this megafloral break to the major floral step change at the traditional Desmoinesian–Missourian boundary and inferred that this coincided with the classic Westphalian–Stephanian boundary in western Europe. As noted above, however, Wagner and Winkler Prins (1985) had earlier moved the definition of the Westphalian–Stephanian boundary to a lower level, correlative within Desmoinesian sections in North America

(Gradstein et al., 2004). This apparent confusion may have arisen, in part, because Peppers (1996, 1997) continued to correlate the traditional Desmoinesian–Missourian boundary with the Westphalian–Stephanian boundary, long after the adoption of the Cantabrian Stage (Wagner and Winkler Prins, 1985). A further inconsistency is that the lowermost Conemaugh Group in the Appalachian Basin, in which Wagner and Lyons (1997) positioned the gap, does not coincide with the major floral step change at the traditional Desmoinesian–Missourian boundary, as Wagner (2003) implied. This event is actually positioned slightly higher in the Conemaugh Group, either between the Mahoning and Brush Creek coals, or between the Mahoning and Mason coals, if the latter is present (Table 1; Kosanke and Cecil, 1996).

Radiometric Age Constraints on the Gap

Despite these uncertainties it is possible nonetheless to ascertain that the Upper Freeport coal, which underlies the gap, is of late Desmoinesian age. Its marine-equivalent Altamont cyclothem (Heckel, 2008) is correlative by means of conodonts to a level just above the current Moscovian–Kasimovian boundary in eastern Europe (Table 1; Heckel et al., 2007). A recent radiometrically based, cycle-calibrated date of 306.65 Ma for the Moscovian–Kasimovian boundary in the Donets Basin of Ukraine (Davydov et al., 2010) provides a date for the base for Wagner and Lyons' (1997) gap. By contrast, mid-Stephanian C megafloral assemblages from the Breitenbach Formation of Saar-Lorraine (Cleal, 2008) have been dated by means of a tonstein at 302.5 ± 0.6 Ma (Fig. 1; Gradstein et al., 2004, recalibrated from 300.3 ± 0.6 Ma in Burger et al., 1997). These dates indicate that a minimum duration of the gap would be around 3–4 myr; however, if the gap extends to the earliest Permian, as has been implied (Wagner and Lyons, 1997; Wagner, 2003), the duration would be even greater. Thus, considering the U-Pb zircon date of 298.9 +0.31/−0.15 Ma (Ramezani et al., 2007) for volcanic tuffs near the Carboniferous–Permian boundary (~mid-Autunian) in the southern Urals, the gap could be as great as 6–7 myr (Fig. 1).

INDEPENDENT BIOSTRATIGRAPHIC CONSTRAINTS ON THE GAP

In the last decade great strides have been made in correlating the glacial-eustatic Middle and Upper Pennsylvanian marine cyclothems of Midcontinent and eastern North America with those in eastern Europe. Those cyclothems are in the Donets Basin of Ukraine and the Moscovian–Kasimovian–Gzhelian succession of the Moscow Basin of Russia, from which the names of the global stages of the Middle and Upper Pennsylvanian Series are derived (Heckel and Clayton, 2006). The tight correlation that has been developed among the three regions has been termed digital because disconformity-separated marine highstand units correlate directly with other highstand marine units rather than with parts of the succession representing lower stands of sea level (Heckel et al., 2007). Correlation is principally based on a conodont biostratigraphic framework, but is supported by most fusulinid and all available ammonoid data (Heckel et al., 2007). A key correlation point is the first appearance datum (FAD) of the conodont *Idiognathodus simulator* (Ellison, 1941), which has nearly global distribution and has been selected as the event horizon for defining the base of the global Gzhelian Stage (Heckel et al., 2008). Given that the marine-based correlation framework (Table 1) extends from the late Desmoinesian (~late Moscovian to early Kasimovian Stage) through the Missourian (~middle and late Kasimovian Stage) into the early Virgilian (~Gzhelian Stage), it can be used to test the megafloral-based correlations of Wagner and Lyons (1997) by providing independent biostratigraphic constraints on their proposed gap.

Testing the Gap Hypothesis at the 7–11 Mine, Ohio

In marshalling evidence for the gap, Wagner and Lyons (1997) were particularly influenced by megafloral assemblages from a single site, the 7–11 Mine in Columbiana County, northeastern Ohio, named for its location near the junction of Ohio highways 7 and 11. The mine has since been reclaimed. From the lower Conemaugh Group in this mine, McComas (1988, 1989) described two megafloral assemblages, 2.4–2.8 m and ~9.0–10.5 m above a late Desmoinesian coal (Fig. 2), now identified as the Upper Freeport coal (see Easterday, 2004, for discussion). Having inferred a late Asturian, or more likely Cantabrian age for the Upper Freeport coal, Wagner and Lyons (1997) re-examined some of McComas' collections and undertook a partial systematic revision. Building on McComas' work, they documented a number of unusual elements including *Taeniopteris, Mixoneura, Walchia,* and *Plagiozamites*, all of which are most abundant in Stephanian C–lower Autunian rocks (Wagner and Lyons, 1997), although several forms are also known from the Barruelian of northwest Spain (Knight, 1974, 1983; Blake et al., 2002).

More recent work has clarified the sedimentological context of these key megafloral assemblages. Easterday (2004) showed that the 7–11 megafloral assemblages came from the base of a broad incised paleovalley, ~1 km wide and at least 10–15 m deep in this area (Fig. 2). The paleovalley cuts down through the latest Desmoinesian Mahoning coal (lowermost Conemaugh Group) to the top of the Upper Freeport coal (which was exposed on the floor of the strip mine) and contains lenses of quartz pebble conglomerate at its base (Easterday, 2004, fig. 3.3). The Mahoning coal is preserved in paleovalley interfluves near the 7–11 Mine, but has been eroded along the valley axis (Fig. 2).

Within the valley fill, two marine zones with rich faunas directly overlie the megafloral assemblages, allowing correlation with other North American and eastern European sections. McComas (1988) regarded the lower unit as the Brush Creek marine zone (BCMZ), but Easterday (2004) reinterpreted it as the older Rock Camp marine zone of Slucher (1989). Subsequent studies, however, have confirmed correlation with the lower BCMZ elsewhere in Ohio and with the type BCMZ in Pennsylvania, because the lower marine unit contains the ammonoid *Pennoceras seamani* (Mapes and McComas, 2010) and the conodont *Idiognathodus cancellosus* (J.E. Barrick, personal communication, 2010), both of which are no older than the BCMZ (Work et al., 2007). The upper marine zone, which is still exposed above the reclaimed mine site, correlates with the Upper Brush Creek marine zone of Ohio and the type Pine Creek marine zone of Pennsylvania because it contains the conodont *I. confragus* (J.E. Barrick, personal communication, 2010), which is no older than the Pine Creek marine zone. Because these two marine zones correlate within the middle part of the traditional Kasimovian Stage (early Missourian) (Table 1), there can be no stratigraphic gap of the magnitude proposed by Wagner and Lyons (1997).

Cyclothem-Calibrated Estimates of the Magnitude of the Actual Gap

It is possible to estimate the magnitude of the actual time gap near the Desmoinesian–Missourian boundary using a cyclothem-based calibration method. Heckel (2008) summarized patterns of minor, intermediate, and major sea-level fluctuations in the Midcontinent Basin, extending from Iowa to Oklahoma, and combined cycles of lesser magnitude around those of major magnitude into groupings. Each cyclothem grouping has a mean duration of ~400 kyr, estimated by dividing the amount of time in the succession by the number of groupings (Fig. 3). Most cycles from minor to major in scale can be recognized in the southern Midcontinent Basin from northern Oklahoma into southern Kansas. Cycles of intermediate and major scale are recognized across the northern Midcontinent (Missouri and Iowa) and in the Illinois Basin, but only the major cyclothems are recorded in the Appalachian Basin. This west-to-east pattern of decreasing completeness of the cyclothem record

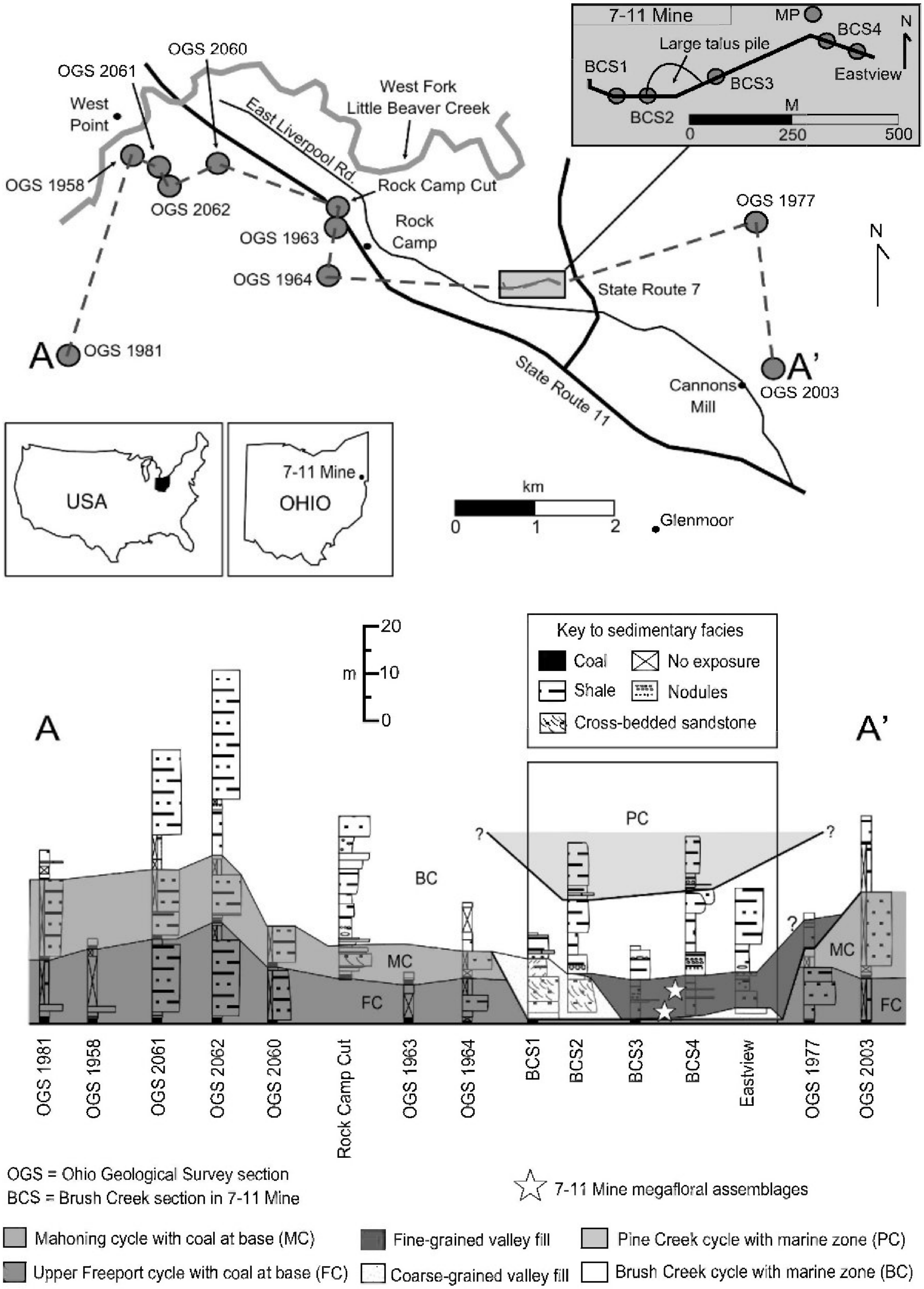

FIGURE 2—Relationship of stratigraphic units exposed at and around 7–11 Mine, Columbiana County, Ohio (S half NW section 13, T 10 N, R 2 W, Madison Township just W-NW of Township Line Cemetery); updated from Easterday (2004, figs. 3.8–3.9). Inset maps show location in United States and Ohio. Names and correlations of marine units are revised based on ammonoids and conodonts collected by G.A. McComas from Brush Creek marine unit and conodonts collected from Pine Creek marine unit by PHH. New Galilee red clay unit outcrops between top of Mahoning cycle and Brush Creek marine unit, ~16 km WNW of 7–11 Mine.

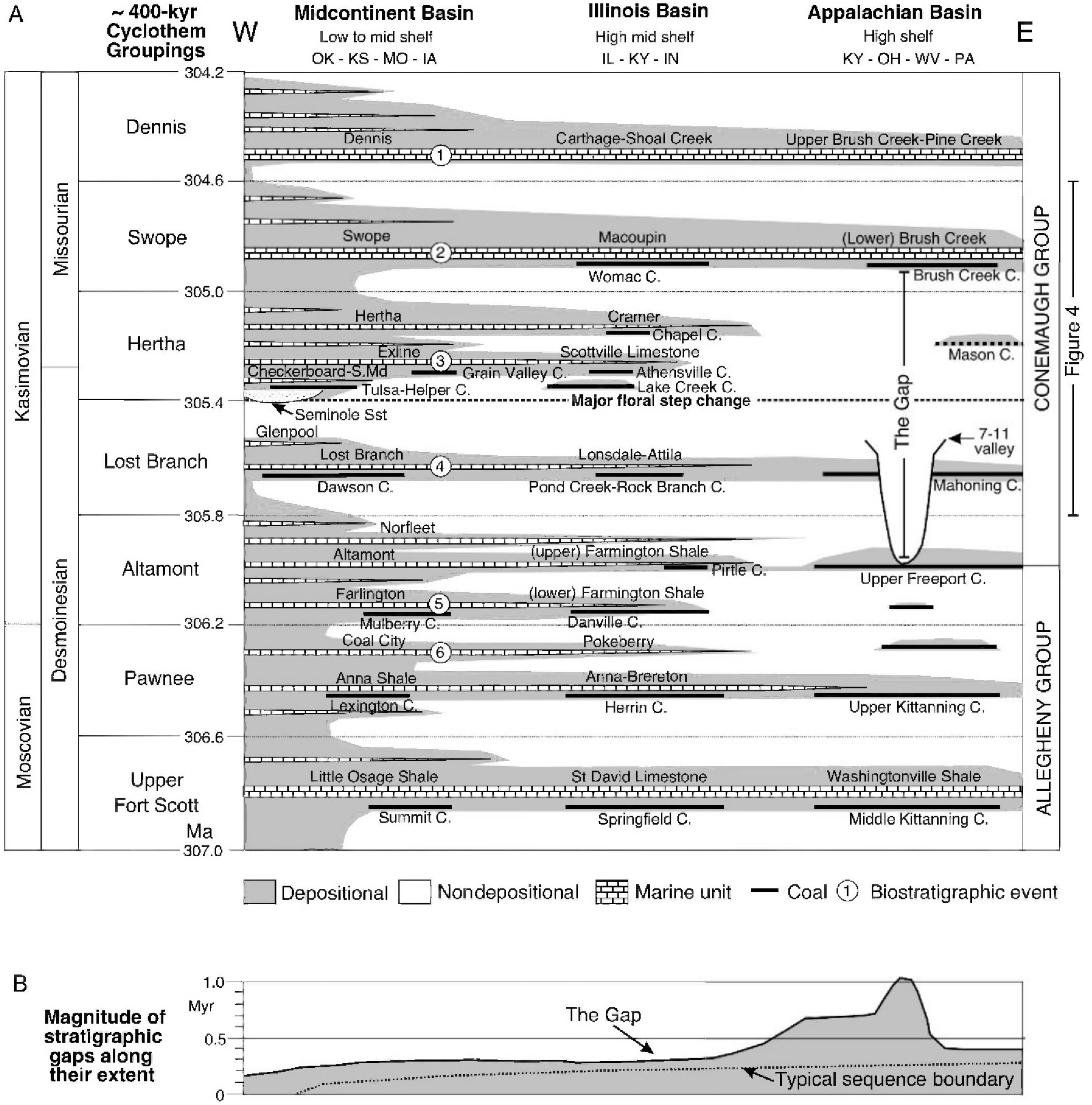

FIGURE 3—Temporal and geographic distribution of stratigraphic gaps in the late Desmoinesian–early Missourian (=late Moscovian–early Kasimovian) of the United States. A) Chronostratigraphic diagram showing correlation of marine units and coals in key cyclothems above and below the gap across central and eastern United States. Correlations are based on conodont biostratigraphic events: 1 = First Appearance Datum (FAD) of *Idiognathodus confragus* in a major cyclothem; 2 = FAD, *I. cancellosus*; 3 = FAD, *I. eccentricus*; 4 = Dominance of *Swadelina nodocarinata* and sole appearance of *Gondolella magna*; 5 = FAD, *S. neoshoensis*; 6 = Last Appearance Datum (LAD) of *I. delicatus*. Vertical scale is based on inferred 400 kyr cyclothem groupings of Heckel (2008). Different names (with dashes) are used in different parts of the basin. C = coal. Mason Coal refers to sparse local coals across the Appalachian Basin in that general position, including those in New Galilee unit. Correlations of lower and upper parts of Farmington Shale and associated coals in the Illinois Basin are not yet completely resolved. Dashed boundary between Moscovian and Kasimovian stages is the one currently used, but is not necessarily the boundary that will ultimately be selected. B) Lateral changes in the magnitude of the gap (in gray) shown in Figure 3A across the basins from west (left) to east and comparison with the average gap seen at a typical sequence boundary.

reflects the starting position, direction of transgression, and degree of expansion of the open sea with each cycle of glacial melting. At glacial maxima, the sea retreated toward the deeper Arkoma-Anadarko Basins of central Oklahoma.

Ice melting and associated global climatic changes resulted in frequent transgressions across the low shelf positioned in Kansas, fewer transgressions across the upper mid shelf and into the Illinois Basin, and even fewer into the Appalachian Basin. Transgressive marine intervals in this latter area were deposited during only the greatest inundations at the times of the warmest interglacials. Thus the Appalachian Basin was on the higher margin of the shelf adjacent to the piedmont of the orogenic highlands at this time (Heckel, 1994). These directions of transgression and regression are strongly supported by east-to-west patterns of cyclothem-associated strata. Extensive paleosols, with or without capping coal beds, separate all marine zones in the Appalachian Basin, nearly all cyclothems in the Illinois Basin, and most cyclothems on the northern (Iowa-Missouri) part of the Midcontinent shelf. Paleosols disappear, however, southward across eastern Kansas until only a few extend to the deeper basin margin of central Oklahoma (Heckel, 2008).

Patterns of Appalachian Sedimentation

The lower Conemaugh Group (from top of Upper Freeport Coal through Ames Limestone) in southernmost Ohio and adjacent parts of West Virginia and Kentucky contains nine paleosol-bounded cyclothems averaging 8 m in thickness (Martino, 2004), of which the lower five are shown on Figure 3. Paleosols that form cyclothem boundaries are mature and distinguished by horizonation, soil structure, and root traces. Incised valley fills from 20 to 35 m thick contain multistory fluvial and estuarine channel facies. The cyclothems are most complete along the paleo-interfluves, where extensive well-drained paleosols that formed during lowstands are used as sequence boundaries (Martino, 2004). Rising base level drowned these paleosols, yielding vertical transitions to coal and lacustrine, or marine shale and limestone. Highstand systems tracts are represented by regressive, coarsening-upward shales and siltstones deposited as sea or lake fills, capped by paleosols. The tops of well-drained vertisols and aridisols represent inferred climate change surfaces (Busch and Rollins, 1984), which equate with marine flooding surfaces.

The interval from the Upper Freeport to the Brush Creek Coal is typically 30 m thick and contains three paleosol-bounded allocycles. The earliest red paleosols typically appear 15–20 m below the Brush Creek coal and are generally absent below this level. The lower red paleosol between the Upper Freeport and Brush Creek coals is inferred to lie just below the Mahoning coal horizon. The upper red paleosol occurs about midway between the Mahoning horizon and the Brush Creek Coal, and is inferred to lie just below the Mason Coal horizon. The paleosols range in thickness from 0.8 to 5.5 m and consist of hackly mudstones with angular, blocky fracture. Peds and cutans are well developed and large conjugate shears with slickensides are common. Horizons grade upward from red and green to dark greenish gray and dark gray; pedogenic carbonate nodules are present in the Brush Creek paleosol interval. These features collectively are characteristically developed in vertisols. The paleosols may represent prolonged time intervals of non-deposition (i.e., diastems). Retallack (2001, figs I3.2–13.3) maintained that 1.5–2-m-thick paleosols developed on alluvium with thick (>1 m) argillic (Bt) horizons, like those in the lower Conemaugh Group (Martino, 2004), may have required prolonged exposure, from 10 to 100 kyr or more. The paleosols and incised valley fills in the Mahoning–Brush Creek interval reported to date (Martino, 2004) are no thicker than those that occur above, in the Brush Creek–Ames interval. Thus, there is no anomaly within the Mahoning–Brush Creek interval to suggest a greater hiatus than elsewhere in the lower Conemaugh Group.

Completeness of the Desmoinesian–Missourian Interval in North America

As noted above, the BCMZ directly overlies Wagner and Lyons' (1997) inferred major gap in the 7–11 Mine (Fig. 2). This marine zone correlates with the Macoupin cyclothem of Illinois and the Swope major cyclothem of the Midcontinent (Fig. 3). Below the BCMZ, the Mahoning and Upper Freeport coals, which are present in and around the 7–11 Mine, correlate with the Lost Branch and Altamont major cyclothems, respectively, of the Midcontinent (Heckel, 2008). These correlations are consistent with palynomorph-based correlation of the Mahoning and Upper Freeport coals with the Dawson and Mulberry coals, respectively, in the Midcontinent (Peppers, 1996). They are likewise correlated with the Pond Creek and Danville coals, respectively, of the Illinois Basin. Moreover, the next stratigraphically lower major marine unit in the Appalachian Basin, the Washingtonville Shale (above the Middle Kittanning coal) is correlated with the Little Osage Shale in the Upper Fort Scott major cyclothem of the Midcontinent (Fig. 3) on the basis of ammonoids (Work et al., 2009).

Accepting the inference that each grouping of lesser cyclothems around a major cyclothem in the Midcontinent represents a ~400 kyr interval (Heckel, 2008), it is possible to estimate the approximate amount of time that is missing between the major units in the Appalachian Basin. Based on correlation of the Missourian BCMZ with the Swope major cyclothem, and the Desmoinesian Mahoning coal with the Lost Branch major cyclothem (Fig. 3), there is only one major 400 kyr cyclothem grouping (the Hertha) that is nearly entirely missing (i.e., has no marine or major coal units) in the Appalachian Basin at the Desmoinesian–Missourian boundary. Where the Mahoning coal is eroded out by valley incision in the 7–11 Mine area, however, two major cyclothem groupings (Lost Branch and Hertha) are missing (Fig. 3), but this larger stratigraphic gap is highly localized in a belt <1 km wide (Easterday, 2004; Fig. 2).

The Hertha 400 kyr cyclothem grouping contains a minor cyclothem (Checkerboard–South Mound) at its base in Oklahoma, but this unit extends northward only into eastern Kansas. The Checkerboard-South Mound is overlain by the intermediate Exline cyclothem, which extends into the Illinois Basin as the Scottville Limestone (Fig. 3). The major Hertha cyclothem, above the Exline cyclothem, extends into Illinois as the Cramer marine unit above the Chapel coal and the Scottville Limestone, but no correlative marine zone is known in the Appalachian Basin. There is a thin local coaly zone reported above a post-Mahoning red paleosol in the New Galilee clay unit (between the Mahoning coal and BCMZ north of the 7–11 Mine in the Ohio-Pennsylvania region) and a similar local coal is termed Mason elsewhere in the basin (Fig. 3). Both may be equivalent to units within the Hertha cyclothem grouping in the Midcontinent Basin.

The Midcontinent interval between the Mahoning and Mason–New Galilee coals of the Appalachian Basin that includes Wagner and Lyons' (1997) gap is the interval between the Lost Branch and Hertha major cyclothems. This interval contains the minor Glenpool cyclothem above the Lost Branch major cyclothem in Oklahoma and southern Kansas (Fig. 3), and the coal known as the Hepler (Kansas) or Tulsa (Oklahoma), which is part of the Checkerboard–South Mound minor cyclothem at the base of the Hertha cyclothem grouping. The paleosol beneath the Hepler-Tulsa coal extends farther basinward than do most others, into the basin margin of central Oklahoma, where it is associated with the Seminole Sandstone, an incised valley fill. Therefore, the gap seen in the Appalachians is still represented in the Midcontinent, but its magnitude seems to be minimal, comparable to the sequence boundaries seen between cyclothems at many levels higher on the shelf during this part of the Pennsylvanian (Fig. 3).

The gap at the base of the Seminole Sandstone in Oklahoma is estimated to be on the order of <200 kyr or less than one half of a cyclothem grouping (Fig. 3). The erosional surface overlain by this sandstone developed when sea level stood extraordinarily low, presumably during a particularly intense phase of glaciation on Gondwana. This diastem became longer (perhaps up to 300 kyr) into the Illinois Basin where the minor Checkerboard–South Mound cyclothem is absent (although possibly represented by the Lake Creek coal), and the minor Glenpool cyclothem is absent in the top of the Lost Branch cyclothem grouping. The intermediate Exline-Scottville marine transgression, however, is still present between the major Lost Branch–Lonsdale/Attila transgression and the major Hertha-Cramer transgression (Fig. 3). The diastem increases to ~600 kyr on the main part of the Appalachian high shelf. Here, the interfluves contain the Lost Branch–equivalent Mahoning coal, but the local Mason–New Galilee coaly zone is typically absent, and the entire interval in the position of the Hertha major cyclothem grouping is represented by paleosols and erosion surfaces developed on terrestrial deposits. In the 7–11 Mine, however, the BCMZ and coal lie not far above the Upper Freeport coal, because the Mahoning coal was cut out during valley incision and two major cyclothem groupings are missing. Here, the time gap is ~1 myr when the adjacent parts of the major groupings this high on the shelf are included (Fig. 3).

Thus, even where most pronounced by local erosion, the time gap is only ~25%–33% of the smaller estimate (3–4 myr) for the gap inferred by Wagner and Lyons (1997) and only ~15% of their larger estimate (6–7 myr). Moreover, the time gap is only of this magnitude in the vicinity of the 7–11 Mine exposure in a belt <1 km wide but of indeterminate length. Outside of this area, over most of the Appalachian Basin, the time gap is typically about an order of magnitude shorter than their larger estimate, and 15–20 times shorter than their smaller estimate in the Midcontinent Basin.

Tight Correlation of North America and Eastern Europe

The independent constraints on the duration of the time gap near the Desmoinesian–Missourian boundary are ultimately based on the tight marine cyclothem correlation framework between the Midcontinent succession and the Moscow and Donets basins (Table 1). The underlying assumption is that these two basins are essentially complete. The implication of this is that if the gap exists across North America, it must also exist with equal magnitude in eastern Europe. The minimum estimate for the gap (3-4 myr) would compress the entire latest Desmoinesian–Missourian–Virgilian and traditional Kasimovian–Gzhelian stages into ~4 myr. These time intervals are presently considered to total about 7–7.5 myr in both North America (Heckel, 2008) and Ukraine (Davydov et al., 2010), based upon independent 400 kyr cyclothem-grouping calibrations, with radiometric age constraints in the Donets Basin and nearby southern Urals. The maximum age estimate for the gap (6–7 myr) would make the Kasimovian and Gzhelian Stages (which constitute the global Upper Pennsylvanian Series) entirely disappear, if the new radiometric age of the base of the Permian (298.9 Ma; Ramezani et al., 2007) is accurate.

A gap of these magnitudes, however, has not been recognized in either of the eastern European regions, nor in the most recent summary of Donets Basin cyclostratigraphy (Davydov et al., 2010). Furthermore, given the different tectonic settings of the Moscow (a cratonic basin like Midcontinent Basin) and the Donets Basins (a rapidly subsiding aulacogenic basin), if a major gap were present, one would expect that the Donets Basin would contain a much more complete record of the Kasimovian–Gzhelian interval. An almost one-to-one correlation of major cyclothems across three basins in two different tectonic settings (Table 1), however, supports the concept that there is no major time gap across the interval of the major floral step change. If the same major gap existed in both the Midcontinent and Moscow cratonic basins, it would be expected to be filled with additional marine units in the rapidly subsiding aulacogenic Donets Basin. However, the Donets not only lacks extra marine units at the position of the major floral step change, it does not even seem to have a marine correlative of the Checkerboard–South Mound cyclothem of the Midcontinent (Table 1). The conclusion of this comparative analysis is that the southern part of the Midcontinent Basin of North America appears to have the most complete section of all these basins across the major floral step change (Fig. 3). While no major gap is known in the eastern Europe basins, however, it is still difficult to demonstrate that this is the case on the basis of biostratigraphy alone due to an inherent circularity of reasoning, i.e., it just might be possible that a gap of similar magnitude could be present in both North America and both tectonic settings of eastern Europe.

EVOLUTIONARY TRENDS ACROSS THE GAP

Is there any way to break this circularity of reasoning and show unequivocally that a gap of long duration does not exist? One approach is to examine evolutionary patterns across the key interval. One might predict that a gap of up to 7 myr would be marked in the stratigraphic record by an abrupt evolutionary discontinuity, with large numbers of different species above and below the boundary. Distribution of marine taxa, including fusulinids, brachiopods, ammonoids, and conodonts (Heckel et al., 2002; Rosscoe, 2008), along with studies of terrestrial plants and tetrapods (DiMichele and Phillips, 1996; Berman et al., 2010; Sahney et al., 2010), show that these groups did experience elevated levels of species extinction at the boundary. As elaborated below, however, this is most parsimoniously explained in terms of ecosystem response to an intense glacial phase, which triggered climatic aridification and a concomitant major withdrawal of the sea at that time.

Of the marine taxa, the highest-resolution evolutionary studies have been carried out on conodonts. Recent detailed study (Rosscoe, 2008; Rosscoe and Barrick, 2009a, 2009b) shows survival of an ancestral species (*Idiognathodus swadei*) from the Desmoinesian Lost Branch cyclothem across Wagner and Lyons' (1997) gap. In the Missourian, this species gave rise to a series of descendants in the various cycles up through the 400 kyr Hertha and Swope cyclothem groupings. This gradualistic evolutionary pattern (Fig. 4) conflicts with an abrupt changeover in large numbers of species that would be expected with a large time gap. The succession of conodont faunas following the gap is so complete that a working group has been engaged in positioning the global Moscovian–Kasimovian boundary within the interval occupied by the Exline and Hertha cyclothems in the Midcontinent (Villa and Task Group, 2008).

In terrestrial settings, as already noted, there is a major, well-documented changeover from lycopsid-dominated coals to those dominated by tree ferns. This step change occurs between the Mahoning coal and its correlatives (Dawson, Pond Creek, and Rock Branch coals) below, and the Tulsa coal and its correlatives (Hepler and Lake Creek coals) and the slightly younger Athensville coal above (Fig. 3). This floral change resulted in the regional disappearance of *Lycospora*-producing arborescent lycopsids in the Appalachian Basin and westwards (Phillips and Peppers, 1984; DiMichele and Phillips, 1996) and a shift in the dominance-diversity pattern of pteridosperms and tree ferns (Pfefferkorn and Thomson, 1982). In the aftermath, there was an interval of time up through the Chapel coal in Illinois, amounting to about one 400 kyr cyclothem grouping, during which the dominance patterns of peat-forming vegetation were highly variable, as if going through a pattern of recovery (Peppers, 1996, 1997; DiMichele and Phillips, 1996; Falcon-Lang and DiMichele, 2010). The dominant plants in these environments during this transitional period, based on palynological analyses (Phillips et al., 1974; Kosanke and Cecil, 1996; Peppers, 1996), were usually herbaceous ferns, lycopsids, or sphenopsids, a pattern consistent with findings that nearly 80% of the tree species turned over at this boundary (DiMichele and Phillips, 1996). Coincident with the major step change in vegetation, there was a phase of rapid diversification among tetrapods (amphibians and reptiles) coupled with an explosion of endemism, probably reflecting habitat fragmentation (Sahney et al., 2010).

These elevated rates of extinction, diversification, and endemism documented across the boundary in both marine and terrestrial groups are adequately explained in terms of ecosystem recovery from an exceptionally intense glacial phase, as indicated by the farther regional withdrawal of the sea following the Lost Branch transgression (Heckel, 1991), which is demonstrated by the presence of deeply incised paleodrainage at this level in the vicinity of the 7–11 Mine. Such a glacial phase would have both limited (and hence stressed) the habitable area for the marine groups. It also would have aridified climate, causing freshwater wetlands to contract, eliminating key hydrophilic taxa, and promoting endemism following habitat fragmentation (Phillips, 1979; Blake et al., 2002; Falcon-Lang and DiMichele, 2010; Sahney et al., 2010). Independent geological evidence for this climate shift includes the appearance of red-colored sediments and vertic and calcic paleosols

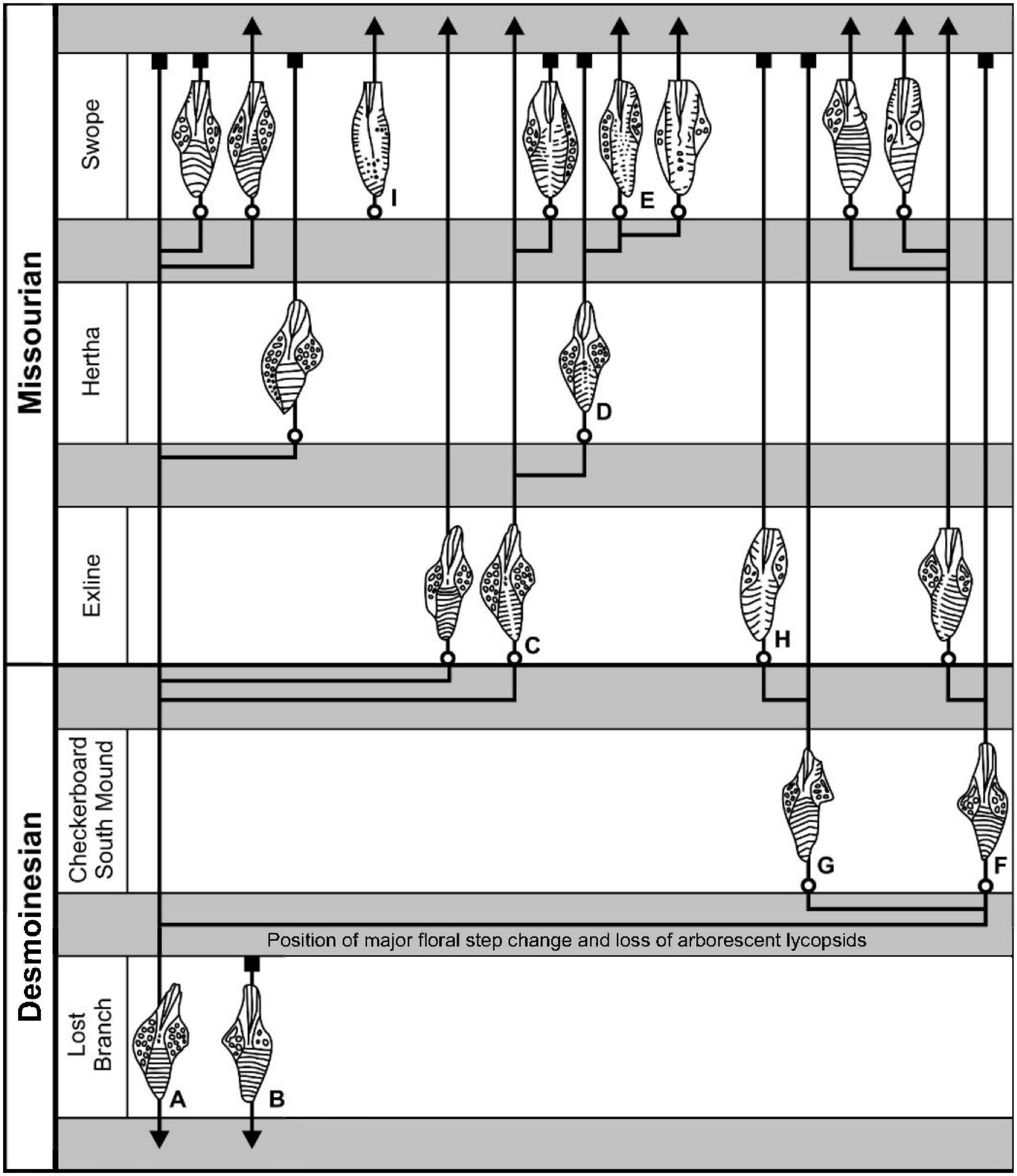

FIGURE 4—*Idiognathodus* diversification from Lost Branch to Swope cyclothems of the Midcontinent Basin (after Rosscoe, 2008; Rosscoe and Barrick, 2009b) within the Kasimovian Stage (spanning Desmoinesian–Missourian boundary). Gray = sequence boundaries separating cyclothems on mid shelf; thick black lines = species ranges, with arrows indicating continuation of range beyond chart; open circles = FAD; closed squares = LAD. Key taxa indicated by bold letters: A = *I. swadei*, B = *I. expansus*, C = *Idiognathodus* sp. Z, D = *I. turbatus*, E = *I. cancellosus*, F = *I. sulciferus*, G = *I. harkeyi*, H = *I. eccentricus*, I = *I. biliratus*.

(e.g., New Galilee clay unit and others associated with the Mason coals) around this level in the Appalachian Basin (Blake et al., 2002; Martino, 2004). In contrast, the patterns are inconsistent with a large time gap, which would have resulted in a sharp evolutionary discontinuity involving large numbers of different taxa on either side of the gap.

ALTERNATIVE INTERPRETATION OF THE 7–11 MEGAFLORAS

Accepting the conodont-based biostratigraphy and evolutionary arguments against a gap of long duration, the Conemaugh megafloras in the 7–11 Mine of Ohio must be no younger than early Missourian–Kasimovian (i.e., ~mid-to-late Cantabrian in age). How can this inference be reconciled with the occurrence of *Taeniopteris, Mixoneura, Walchia*, and *Plagiozamites*, among other taxa, which were used to imply a much younger age (Wagner and Lyons, 1997)?

Paleoclimatic Context

The key to resolving this paradox is a detailed understanding of the paleoclimatic context of the 7–11 megafloral assemblages. Easterday's (2004) re-examination of the original field notes provided a basis from which to determine the sedimentologic and sequence-stratigraphic context of the contentious megafloras. The lower megafloral assemblage was collected from sideritized beds in gray shale positioned from 2.4 to 2.8 m above the Upper Freeport coal (McComas, 1988, 1989). This came, at least in part, from the lower part of the valley-fill succession, which contains a nonmarine fauna (McComas and Mapes, 1988). As the roof shale of the Upper Freeport coal is locally preserved beneath the base of the paleovalley (Easterday, 2004), however, it is possible that some of the megafloral specimens also may have been collected from this unit, resulting in a stratigraphically mixed collection. Examination of the taxonomic list for this assemblage suggests that this scenario is likely, with elements characteristic of the Upper Freeport coal roof shale at other sites (Wagner and Lyons, 1997) intermixed with the more unusual elements. The second megafloral assemblage occurs higher in the valley-fill succession within a dark-gray shale, ~1.5 m thick, positioned directly below the early Missourian–Kasimovian BCMZ. It contains a distinctive, lacustrine biota (Easterday, 2004). Within this framework, the lowermost megafloral assemblage consists of a mixture of older transgressive (roof shale) and lowstand (valley-fill) sources, whereas the upper megafloral assemblage was derived from swamps and lakes developed prior to a major marine transgression.

The incised valley fill in which the 7–11 megafloral assemblages are preserved is the sedimentary expression of the major post-Mahoning/Lost Branch sea-level drawdown caused by an intense glacial phase, which moved the shoreline at least 1500 km to central Oklahoma. The BCMZ in the upper valley-fill succession represents a marine transgression caused as sea-level rose during a later major interglacial phase. Thus, except for material possibly derived from the roof shale of the Upper Freeport coal, both 7–11 megafloral assemblages in the lower valley fill represent vegetation growing around the time of glacial maximum conditions, or at the very least prior to major deglaciation and the full onset of interglacial conditions. As such, these unusual floras grew under considerably different climatic conditions from those represented by the wet-climate histosols (coal beds). They more likely are representative of plants growing on the vertic and calcic paleosols occurring between coal beds (DiMichele et al., 2010a; Falcon-Lang and DiMichele, 2010).

Glacial Cycles and Megafloral Biostratigraphy

Glacial-interglacial cycles not only influenced sea level, but also caused major fluctuations in climate (Tandon and Gibling, 1994; Flint et al., 1995; Hampson et al., 1999; Montañez et al., 2007; Poulsen et al., 2007; Tabor and Poulsen, 2008), and consequently in the composition of Pennsylvanian tropical vegetation (Falcon-Lang, 2004; Driese and Ober, 2005; Feldman et al., 2005; Falcon-Lang et al., 2009; Falcon-Lang and DiMichele, 2010). During interglacial phases (late transgressive to highstand systems tracts), climate was largely humid to subhumid, and tropical forests were dominated by lycopsids, pteridosperms, and tree ferns (DiMichele and Phillips, 1994; DiMichele et al., 2001, 2007). In contrast, at intervals approaching glacial maxima, climate was relatively drier and more seasonal, dominated by a variety of gymnosperms that included cordaitaleans, pteridosperms, and conifers (Falcon-Lang et al., 2009; Falcon-Lang and DiMichele, 2010).

These insights, combined with the recognition that some taxa clearly evolved in dryland-upland environments before spreading into wetland ecosystems (Stopes, 1914; Elias, 1936; Moore et al., 1936; Cridland and Morris, 1963; Cridland et al., 1963; Knight, 1974, 1983; Broutin et al., 1990; DiMichele and Aronson, 1992; Blake et al., 2002; Falcon-Lang and Miller, 2007; DiMichele et al., 2008), immediately raise major problems for biostratigraphic practices utilizing megafloral elements without consideration of the paleoenvironmental context. Clearly, for the purposes of accurate time-significant biostratigraphy, it is essential that wetland (interglacial) assemblages are compared only with other wetland assemblages, and dryland (glacial) assemblages are compared only with other dryland assemblages (isotaphonomic assemblages of Behrensmeyer et al., 2000).

To date, few assemblages representing the subhumid to seasonally dry parts of the climate cycle (periods of retreating sea level during early glacial phases to times of lowstand) have been described in the literature because of taphonomic bias, as megaflora are less likely to be preserved in dryland settings (e.g., Leary and Pfefferkorn, 1977; Falcon-Lang, 2004; Feldman et al., 2005; DiMichele and Gastaldo, 2008; Falcon-Lang et al., 2009; Falcon-Lang and DiMichele, 2010; Dolby et al., 2011). Pennsylvanian biozonation in practice has been consistently based on wetland (interglacial) assemblages. It is probable that at least some of the elements in the 7–11 megafloral assemblages, in particular those interpreted as being anomalously young (Wagner and Lyons, 1997), represent remains of plant communities that grew under seasonally dry climates.

Applying the traditional biostratigraphic approach could yield an anomalously young age for these megafloras, because key taxa may have evolved much earlier (in poorly preserved environments) than their appearances in abundance in the fossil record might suggest. Conifers, which occur in the 7–11 Mine flora (Wagner and Lyons, 1997), are known from a few, isolated occurrences beginning in the Middle Pennsylvanian (Scott and Chaloner, 1983; Lyons and Darrah, 1989; Hernández-Castillo et al., 2001, 2009; Scott et al., 2010) and their pollen is encountered even earlier in the late Mississippian (Stephenson et al., 2008; Utting and Giles, 2008; DiMichele et al., 2010a). Yet, conifers do not become common elements of lowland tropical floras until near the Pennsylvanian–Permian boundary (DiMichele et al., 2010b). The rise to dominance of these plants does not reflect an evolutionary replacement of the earlier dominant wetland elements within an isotaphonomic framework. Rather, it reflects a general trend of climatic drying in the equatorial-tropical regions during the Late Pennsylvanian and Early Permian. Similarly, the local occurrence of *Taeniopteris*, *Walchia*, *Dichophyllum*, and *Callipteris* in dryland facies at multiple sites in the Missourian and Virgilian (Upper Pennsylvanian) cyclothems of the Midcontinent (Elias, 1936; Cridland and Morris, 1963; Cridland et al., 1963; Leisman et al., 1988) supports the concept that their distribution was controlled not only by stratigraphy but also by paleoecology.

It follows that the biostratigraphic reasoning used by Wagner and Lyons (1997) to posit a late Stephanian C or early Autunian age for the 7–11 megafloras is problematic because they tried to integrate dryland plant taxa within a wetland-based biostratigraphy. Furthermore, the sequence-stratigraphic context and closely linked paleoclimatic signals of the 7–11 lower Conemaugh megafloras adequately explain why they have the appearance of western European late Stephanian–mid-late Gzhelian assemblages, but are overlain by traditional early Missourian–Kasimovian marine faunas. Ongoing searches are now showing that such dryland (glacial) floras which may appear anomalously young when compared to wetland floras are actually more common in the fossil record than previously thought (e.g., Feldman et al., 2005; Falcon-Lang et al., 2009; Hernández-Castillo et al., 2009; Dolby et al., 2011).

POSSIBLE REASON FOR SCARCITY OF EARLY STEPHANIAN FLORAS

While placement of the 7–11 megafloras within a sequence stratigraphic context may explain the existence of anomalously young assemblages and remove the major support for the presence of a substantial time gap in North America, it does not resolve the secondary contention that early Stephanian megafloras have not been positively identified in the Appalachian Basin and in most other parts of North America (Wagner and Lyons, 1997). Based on an analysis of the literature (principally from Gillespie and Pfefferkorn [1979], a biostratigraphic review of the U.S.G.S.-proposed Pennsylvanian stratotype), Wagner and Lyons (1997) argued that unequivocal early Stephanian megafloras were entirely absent in the Appalachian Basin. To reconcile this idea with our hypothesis that the succession is essentially complete at the level of cyclothem groupings (Fig. 3), two points must be taken into consideration: data quality and paleobiogeography.

Variable Quality of Plant Fossil Datasets

As recognized by Wagner and Lyons (1997), there has been a relative dearth of high quality systematic studies of Pennsylvanian megafloras from key North American intervals and regions. Although fossil plant material is abundant throughout the Middle and Late Pennsylvanian (e.g., DiMichele et al., 2007), encyclopedic systematic compilations of the kind undertaken for the western European region have not been reproduced in North America to the same degree. Notable exceptions include Gillespie et al. (1978), Goubet et al. (2000), Blake et al. (2002), Bashforth (2005), Wittry (2006), and DiMichele et al. (2010a). Conversely, there have been relatively few palynological studies of the western European Stephanian compared to the much better-sampled Late Pennsylvanian of North America (Peppers, 1996, 1997; Eble, 2002; Eble et al., 2003). To the extent to which they are present in both regions, palynofloras are generally similar, although North American assemblages lack the abundant conifer pollen typical of Permian successions in western Europe, a lack especially notable in the Dunkard Group (Clendening, 1972, 1974, 1975), which contains the youngest beds in the Appalachian Basin. Thus, unequal study of megafloral and palynofloral assemblages on either side of the Atlantic may in part have inhibited complete biostratigraphic correlation of the two areas.

Paleobiogeography

A second and more significant reason for the apparent absence of early Stephanian megafloras is subtler, reflecting regional paleobiogeography (Pfefferkorn and Gillespie, 1980). It is significant that the only basin in the United States in which Wagner and Lyons (1997) recognized megafloras that possibly represent the Barruelian or Stephanian B, is the Narragansett Basin of Rhode Island–eastern Massachusetts in southeastern New England. This basin is on the southeastern side of the highly metamorphosed core of the Appalachian orogenic highlands (Skehan et al., 1979), i.e., on the same side as the type Cantabrian and Barruelian substages of northern Spain and thus in close biogeographic connection with the area on which much of the megafloral biostratigraphic reasoning was based. Similarly positioned east of the Appalachians is the Sydney Basin (Gibling et al., 2004) of Nova Scotia, Canada, where widespread Cantabrian megafloras have also been recognized (Cleal et al., 2003).

Factors including climate, geography, and orography profoundly influence the distribution of plant taxa today, giving rise to a patchwork of intergrading floral provinces within a biome (Walter, 1973; Breckle, 2002). Such partitioning has been identified for the Late Pennsylvanian landscape, with orogenic and climatic barriers key to maintaining provincialism (Blake et al., 2002). Pfefferkorn and Gillespie (1980) demonstrated that such provinces existed within the humid tropical biome in North America during the Pennsylvanian (Fig. 5), and their Acadian and Interior Appalachian provinces illustrate just such a difference. Tenchov and Cleal (2010) quantitatively demonstrated east-west gradients of plant biogeography across the Euramerican floral realm for the Bashkirian and early Moscovian stages. The data presented by Pfefferkorn and Gillespie (1980) indicated that the degree of difference and potentially even provincial boundaries might have changed throughout the Pennsylvanian. It appears that the Cantabrian–Barruelian-type megafloras characteristic of the eastern side of the Appalachian orogenic belt may represent one such Pennsylvanian floral province (Acadian on Fig. 5). This province would have shared many taxa with central and eastern Pangea, but also contained an array of distinctive elements. Floristic comparisons with these floras add an extra layer of uncertainty to the use of megafloras for biozonation because key index species in the stratotypes of northern Spain may not have colonized the western side of the Appalachians or those colonization events may have been diachronous (Laveine et al., 2000).

To give Pennsylvanian examples of the problematic issues raised by floral provincialism, consider the Langsettian regional substage. This unit is thickest and best developed in the Black Warrior Basin of Alabama, United States, where it is recognized by the common presence of *Sphenopteris pottsvillea*; however, this key taxon is found solely in the Appalachian Basin (Gastaldo and Boersma, 1983a, 1983b; Gastaldo et al., 2004) and is absent from time-equivalent basins in western Europe. If this taxon had been used to circumscribe the biostratigraphy of the Langsettian, this substage would be considered absent in the western European floral record. In addition, medullosan foliage of *Macroneuropteris scheuchzeri* has a range that terminates at the end of the Cantabrian in western Europe, but continues until at least the end of the Pennsylvanian in North America (Pfefferkorn and Gillespie, 1980; Blake et al., 2002). Clearly there were profound biogeographic barriers to the migration of certain species across or through the Variscan-Appalachian mountain belt, and extirpation of a few common species did occur at different times in different areas.

Thus, it is important to use caution when employing palynofloral or megafloral biozonation for correlation, especially where the regions to be correlated are disjunct. In those cases, biostratigraphic correlation is more precise if it relies on the sequence of first and last appearance data of those taxa common to both areas (Blake et al., 2002; Pfefferkorn, 2003; Sadler, 2004), and eliminates taxa that have shown slow migration over time (Laveine et al., 2000; Blake et al., 2002) or regional extirpation (DiMichele et al., 2009).

PENNSYLVANIAN OF MARITIME CANADA

In the preceding argument, disparate pieces of evidence have been summarized to support the hypothesis that no major gap exists in the Appalachian Basin and particularly in those basins to the west. Wagner and Lyons (1997) also inferred the gap to be present in the Canadian Maritime Basin, east of the Appalachians, however. Specifically, they positioned the gap between the Point Aconi coal of the early Cantabrian Sydney subbasin (Cleal et al., 2003) and a red bed succession 200–300 km away on Prince Edward Island, whose age is uncertain but probably spans the Pennsylvanian–Permian boundary (Gibling et al., 2009).

Inference of the gap between these two rock units seems to have resulted from misinformation about the regional geology of Maritime Canada at the time. The Point Aconi coal represents the youngest Pennsylvanian unit of the Sydney Mines Formation preserved onshore in the Sydney subbasin, but this formation also extends offshore where it has been extensively cored (Gibling et al., 2004). A thick and conformable stratal succession overlies the Point Aconi coal offshore including at least one younger coal, the Murphy coal. Examination of seismic profiles and palynological assemblages from core indicates that this offshore succession extends without a detectible break (Pascucci et al., 2000) well up into the Late Pennsylvanian (Barruelian–Stephanian B; Dolby, 1989), perhaps as far as the Permian (Giles and Utting, 1999).

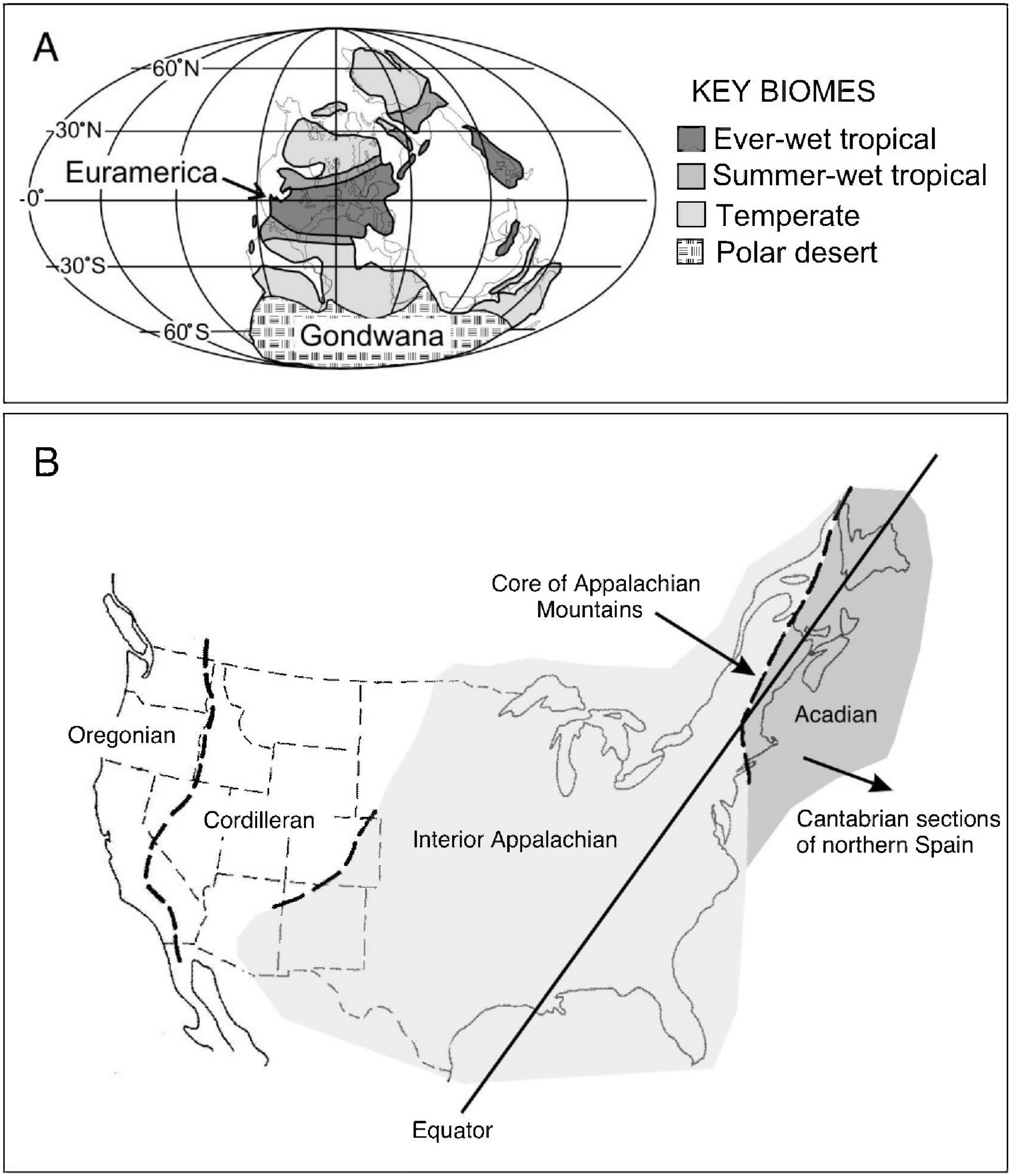

FIGURE 5—Pennsylvanian biomes and plant paleobiogeographic provinces. A) Key global biomes (Falcon-Lang, 2004); B) North American provinces (modified from Pfefferkorn and Gillespie, 1980) showing position of Acadian Province containing western European elements on paleo-SE side of Appalachian mountain belt. Interior Appalachian Province on paleo-NW side shows clear floristic differences, especially during certain time intervals. Cordilleran and Oregonian provinces are not directly relevant to issues addressed in this paper.

A profound angular unconformity exists at the approximate level of the gap in several parts of the Gulf of St. Lawrence, however. In these places, a ~700-m-thick succession of Permian sandstone and shale disconformably overlies Mississippian to Middle Pennsylvanian rocks, but these are highly localized contacts demonstrably related to exhumation adjacent to halite diapirs (Alsop et al., 2000). Thus while localized unconformities are present and linked to salt tectonics in parts of the Maritime Basin, there is no evidence for a widespread gap and there are some places where Late Pennsylvanian strata have been positively identified.

CONCLUSIONS

1. Conodont-based correlation of Middle to Upper Pennsylvanian marine strata representing sea-level highstands between North America and two tectonically different regions in eastern Europe demonstrates that all successions are generally complete enough to be correlated. Thus, the regional North American Missourian and Virgilian Stages correlate quite closely with the eastern European (and global) Kasimovian and Gzhelian Stages, respectively.

2. Correlation of ~400 kyr cyclothem groupings around the Desmoinesian–Missourian boundary in North America shows that only a relatively minor disconformity (perhaps up to 600 kyr) is evident across much of the Appalachian Basin, although it is greater in the vicinity of the 7–11 Mine in Ohio (~1 myr) due to paleovalley incision. This relatively minor gap in the Appalachian Basin, which resulted from an extreme sea-level drawdown caused by an intense glacial phase, becomes progressively filled by marine units basinward toward the southern Midcontinent, where it is reduced to <200 kyr.

3. Patterns of high species turnover among marine and terrestrial taxa around the Desmoinesian–Missourian boundary in North America are not necessarily indicative of the existence of a large stratigraphic gap. Rather, the conodonts in particular are best explained in terms of ecosystem recovery from a crisis induced by an unusually intense glacial phase and sea withdrawal, followed by subsequent warming and transgression. If patterns were the result of a large time gap, one would expect to see a greater degree of evolutionary discontinuity involving large numbers of different taxa on either side of the gap.

4. Sequence-stratigraphic reasoning applied to Wagner and Lyons' (1997) biostratigraphic dataset suggests that they compared megafloras that grew during humid climate intervals (prior to and during highstands) with those that had their genesis during more strongly seasonally dry phases around the times of sea-level lowstand. Such comparisons probably led to incorrect biostratigraphic inferences.

5. The apparent near-absence of many Cantabrian, any Barruelian, or Stephanian B megafloras in most of North America, except in the Narragansett Basin of southeastern New England and the Sydney Basin of Nova Scotia, is likely a paleobiogeographic effect. The similarities between the megafloral assemblages of these two basins and the Cantabrian region of Spain are more likely related to the paleogeographic position of both North American basins on the southeastern side of the major orogenic highland belt, closer to the type Cantabrian and Barruelian of northern Spain.

6. The multifaceted findings summarized in this paper falsify the hypothesis that a major (3-4 or 6–7 myr) disconformity occurs near the Desmoinesian–Missourian boundary in North America, as inferred by Wagner and Lyons (1997) based on megafloral assemblages at the 7–11 Mine, Columbiana County, Ohio, and on the apparent absence of earlier Stephanian megafloras at other North American sites.

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