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ECOLOGICAL PERSISTENCE IN THE LATE MISSISSIPPIAN (SERPUKHOVIAN, NAMURIAN A) MEGAFLORAL RECORD OF THE UPPER SILESIAN BASIN, CZECH REPUBLIC

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ABSTRACT

The Serpukhovian (Namurian A) stratigraphy of the Ostrava Formation, Upper Silesian Coal Basin, Czech Republic, consists of coal-bearing paralic sediments underlain by marine deposits in a cyclothemic nature similar to those in the Pennsylvanian of Euramerica. The thickness of the formation exceeds 3000 m, in which >170 coals are identified in a foreland basin setting. Fifty-five genetic cycles are identified in the present study, using transgressional erosional surfaces as lower and upper boundaries. Terrestrial plant-macrofossil assemblages are preserved within each cycle, mostly associated with coals, and these represent a sampling of the coastal plain vegetation. New high-precision isotope dilution–thermal ionization mass spectrometry U-Pb ages on zircons from tonsteins of two coals provide chronometric constraints for the Serpukhovian. Unweighted Pair Group Method with Arithmetic Mean clustering and Bayesian statistical classification group macrofloral assemblages into four distinct stratigraphic clusters, with assemblages persisting for <18 cycles before compositional change. Cycle duration, based on Ludmila (328.84±0.16 Ma) and Karel (328.01±0.08 Ma) tonsteins, overlaps the short-period (100 kyr) eccentricity cycle at the 95% confidence interval. These dates push the beginning of the Serpukhovian several million years deeper in time. An estimate for the Visean-Serpukhovian boundary is proposed at ~330 Ma. Late Mississippian wetland ecosystems persisted for >1.8 million years before regional perturbation, extirpation, or extinction of taxa occurred. Significant changes in the composition of macrofloral clusters occur across major marine intervals. These results accord with other estimates of Carboniferous tropical wetland community persistence. Hence, vegetational persistence was characteristic of peat-accumulating and mineral-substrate wetland ecosystems beginning in the Late Mississippian, when there is evidence for the first appearance of eustatically controlled cyclothems during the buildup of Gondwanan glaciation.

INTRODUCTION

The Late Paleozoic Ice Age is the only time in Earth history, other than the Neogene, when vegetated land masses were subjected to climate fluctuations associated with extended intervals of polar glaciation. Evidence indicates that Southern Hemisphere glaciation began in the Late Devonian (Caputo, 1985; Fielding et al., 2008) and may have been in response to the evolution of gallery forests, concomitant pedogenesis, and a fundamental change in geochemical cycles (Algeo and Scheckler, 1998). The onset of glacial eustasy, as reflected in high frequency sea-level oscillations in the Mississippian, is interpreted to have begun in the mid-Visean of Britain (Wright and Vanstone, 2001) and somewhat later in eastern North America (Smith and Read, 2000) and the Illinois Basin (Smith and Read, 2001). Overall, there appears to have been Mississippian cooling and warming (Iannuzzi and Pfefferkorn, 2002) prior to maximum glaciation at the mid-Carboniferous boundary that is evidenced from stable-isotope data recovered from brachiopod shells (Mii et al., 1999).

Our understanding of the response of Carboniferous tropical vegetation to the onset of the Late Paleozoic Ice Age is based on temporally and spatially scattered Mississippian data (e.g., Jennings and Thomas, 1987; Tidwell et al., 1992; Raymond, 1996). Within the Euramerican province, early Visean plant-fossil assemblages consisting of permineralized wood are interpreted to indicate vegetation that grew under temperate conditions with monsoonal rainfall prior to glacial onset (Falcon-Lang, 1999). Beginning in the late Visean and dominating the Serpukhovian, the stratigraphic record of the paleoequatorial belt consists of cyclical terrestrial and marine deposits, including well-developed peat mires (economic coals; e.g., Havlena, 1986).

The Upper Silesian Basin of the Czech Republic and Poland possesses the most complete record of Visean–Serpukhovian–Bashkirian cyclothems in the Euramerican tropics (Fig. 1). Well preserved plant-megafossil assemblages, which occur both within the terrestrial and marine deposits, have been studied intensely since Sternberg (1820–1838). It was recognized early that a dramatic floral turnover occurred during this interval (e.g., Gothan, 1913; Havlena, 1982), which led Gothan (1913) to introduce the term Florensprung for this change across the Mississippian-Pennsylvanian boundary. This change is reflected in Early Pennsylvanian megafloras of the paleoequatorial region, which show a marked increase in diversity when compared with those of the Late Mississippian. This is true in all plant clades following the mid-Carboniferous eustatic event (Raymond, 1996). The extinctions and biotic replacements were used to subdivide the sequence in the Ostrava-Karviná coal field biostratigraphically (Havlena, 1977), in which Purkyňová (1977) distinguished three floral zones in the early Namurian (Serpukhovian = Namurian A).

Coal mining in the Ostrava-Karviná coalfield began in the late 18th century, but increased exploitation followed World War II, connected to the economical and political development of the former Czechoslovakia (Martinec and Schejbalová, 2004). In the course of exploration for coalfield development, ~1200 deep, continuous boreholes were drilled from 1953 to 1998. Each borehole was investigated in detail, and geological survey reports included high-resolution stratigraphic, sedimentological, paleontological, palynological, coal petrographical, geochemical, and (less often) petrophysical data. Presently, finalized borehole reports are housed at the Czech Geological Survey–Geofond (www.geofond.cz), with copies of borehole logs and macrofloral data retained at the Silesian Regional Museum in Opava, Czech Republic.

The suite of megafloral elements preserved within any cyclothem represents a sampling of the vegetation contributing biomass to those fossil assemblages. A comparison of megafloras from cyclothem to cyclothem provides a means by which ecological patterns of persistence and turnover can be identified in the stratigraphic record (DiMichele and Gastaldo, 2008). Such patterns of persistence, perturbation, and ecological change have been documented in the Late Pennsylvanian (e.g., DiMichele et al.,

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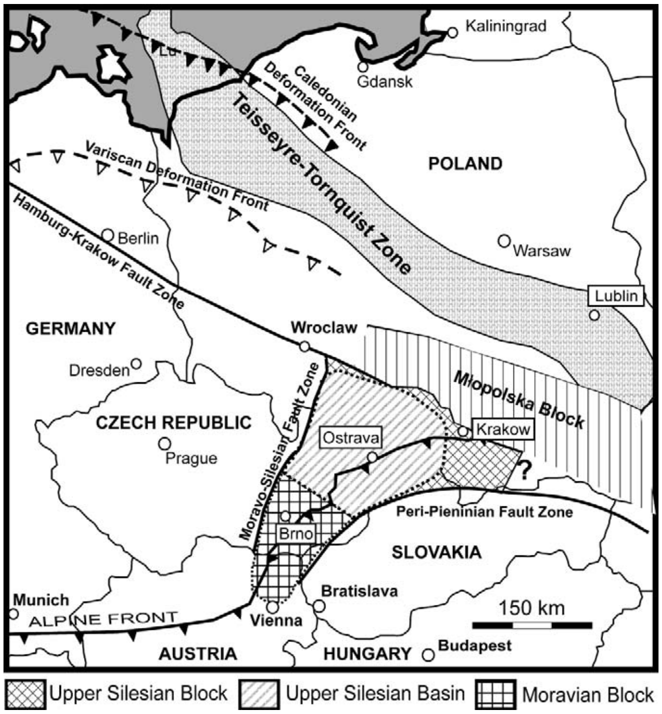


FIGURE 1—Map of central Europe showing the location of the Upper Silesian basin within tectonic context (after Dopita et al., 1997).

1996, 2002) and Permian (DiMichele et al., 2006). A subset of borehole data from the Upper Silesian Basin has been compiled and analyzed using multivariate analyses in an effort to determine if similar patterns of persistence occurred in the Late Mississippian prior to the mid-Carboniferous event.

GEOLOGICAL SETTING

The Upper Silesian Basin is a foreland basin formed during the late Paleozoic as part of the European Variscan fold belt (Fig. 1). Coeval basins of various tectonic styles (e.g., strike-slip and rifting in the Cumberland Basin, Nova Scotia; see Rygel and Gibling, 2006) developed along the margins of equatorial Euramerica, stretching from the southern Appalachians (Black Warrior Basin) to the Ukraine (Donbass Coal Basin). The Upper Silesian Basin lies at the eastern margin of the Variscan Bohemian Massif and is a transitional geotectonic unit between the Variscan orogen and the epi-Cadomian platform (Dopita and Kumpera, 1993). The southern part of the basin lies beneath the Carpathian flysch nappes (Dvořák et al., 1997) with the remainder found at more shallow depths in the Czech Republic and Poland. The entire basin extends over an area of ~6500 km^2, with about one third of that (1800 km^2) in the Ostrava-Karviná coalfield of the Czech Republic. The complex tectonic history is well documented (Kotas, 1982, 1985; Kumpera and Martinec, 1995; Kumpera, 1997), with the recognition that the geometry of the basin changed in response to tectonics associated with oblique collision along with the progradation of a thrust-and-fold belt (Dopita and Kumpera, 1993).

The latest Visean to Serpukhovian (Namurian A) deposits are >1500 m in thickness in the northwest with >3200 m of clastic sedimentation within the depocenter (Dopita and Kumpera, 1993; Kumpera and Martinec, 1995). The total thickness of the Serpukhovian–Moscovian (Namurian A–Westphalian D) succession in the Polish part of the basin is >4600 m thick (Zdanowski and Zakowa, 1995). Deposition of the latest Visean to Serpukhovian paralic sequence (Namurian A, Ostrava Formation) occurred within a mobile foredeep setting (Kumpera and Martinec, 1995) in which cyclothemic sequences of fossiliferous marine deposits are overlain by fossiliferous and coal-bearing continental rocks. Fully continental coal-bearing molasse deposits of Bashkirian (Namurian B–Westphalian A) age attain thicknesses >1000 m (Karviná Formation; see Kumpera and Martinec, 1995). Here, coal-bearing intervals overlie fining-upward sequences of coarse-clastic fluvial regimes that, in turn, are truncated by fluvial incision and a return to coarse clastic deposition (Dopita et al., 1997).

Ostrava Formation

The stratigraphic distribution of sediments in the Ostrava Formation consists of cyclical coal-bearing continental and fossiliferous marine deposits of a paralic nature (Havlena, 1986; Dopita and Kumpera, 1993). Continental siliciclastic lithologies include sandstone of various grain-size and mineralogical character (Kumpera and Martinec, 1995), siltstone, claystone with volcaniclastics (tonstein and whetstone from rhyodacite-dacite and andesite provenances; see Martinec and Jakubec, 2002), and biogenic lithologies as minor components (Kožušníková et al., 2002). Coarse-grained sandstone and conglomerate occur infrequently. Eighty-six economic coals are exploited from these rocks (Martinec et al., 2002) and range from high volatile bituminous A to semianthracite rank; more than 170 individual coals have been recognized (Dopita and Kumpera, 1993). These coals formed in a range of mire types from ombrogenous peats, in which there is high systematic diversity, to lower-diversity densospore-dominated bogs (C. Eble, personal communication, 2007). Nearshore and open marine deposits principally are fine-grained sandstone and siltstone; no limestones are reported in the sequence. Marine invertebrates preserved in these rocks are assigned to E$_1$, E$_{2a}$, and E$_{2b}$ (Gaebler horizon) goniatite zones (Pendleian, Arnsbergian; see Dopita and Kumpera, 1993). There is evidence for reworking of Ostrava Formation coal into the overlying Karviná Formation, indicating that Mississippian deposits were uplifted and eroded in the Pennsylvanian (Kožušníková et al., 2002).

The Ostrava Formation is subdivided stratigraphically into the lowermost Petřkovice Member, overlain by the Hrušov, Jaklovec, and Poruba Members, each of which are several hundred meters thick (Figs. 2, 3). The mid-Carboniferous boundary hiatus occurs at the top of the Poruba Member with the first thick coal of the Karviná Formation (Prokop Seam) overlying the contact. Thick fossiliferous marine deposits, each consisting of a group of marine horizons occurring basinwide, are used to separate the stratigraphic units (Fig. 3). There are ~180 invertebrate intervals identified within siltstones overlying coals, interpreted to represent either freshwater, estuarine, or open-marine assemblages (Řehoř and Řehořová, 1972; Tabor, 1995). In general, facies changes occur toward the east and south and include a decrease in the number and thickness of coals eastward and southward and a decrease in the thickness of the marine intervals eastward (Dopita and Kumpera, 1993). An increase in sandstone grain size and number of conglomerates occurs to the south, indicative of a siliciclastic source in this part of the basin (Kumpera, 1997).

Ostrava Formation Cyclothems

The cyclical nature of the Ostrava Formation was recognized by Havlena (1964), who identified terrestrial and marine cycles that together were grouped into megacyclothems (Dopita and Havlena, 1977). Terrestrial cycles range from 6 m to 20 m in thickness (average = 15 m; see Dopita and Kumpera, 1993). Individual marine zones may range from 32 m to 240 m (Skoček, 1991), depending upon their geographic position in the basin. Megacycles range up to several 100 m and are separated by thick basinwide marine zones (Štúr, Leonard, Naneta, Františka, Enna, Barbora, and Gaebler; see Dopita et al., 1997).

Havlena (1986) used the model of Duff et al. (1967) to circumscribe an ideal terrestrial cycle that was bounded by erosional surfaces. The model placed a coarse clastic (conglomerate or sandstone) unit overlying

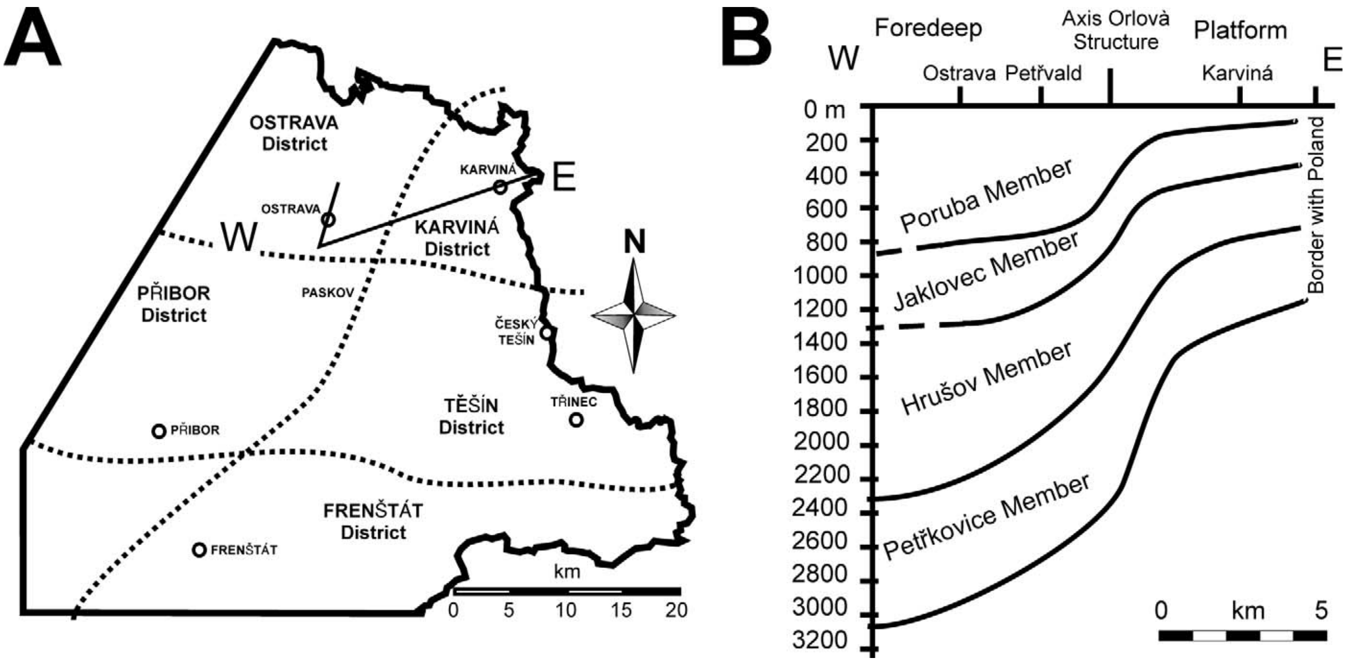
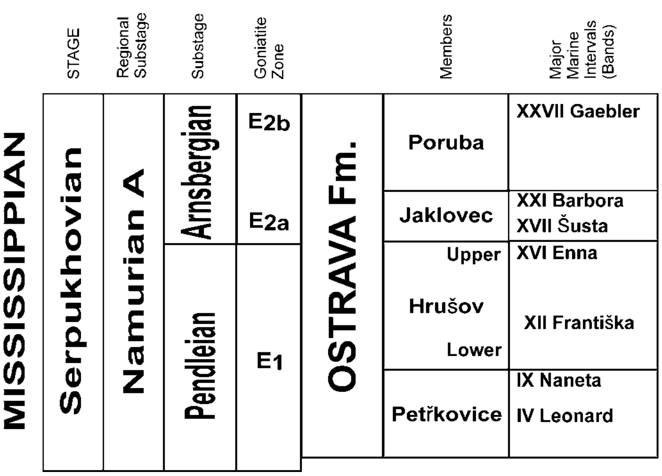


FIGURE 2—Map of the Ostrava-Karvina coalfield. A) Mining districts from which borehole data were acquired are outlined; the W–E line depicts the basinal cross section shown in B. B) Distribution and thickness of coal-bearing members of the Mississippian Ostrava Formation in stratigraphic order (after Pešek et al., 1998).

an erosional contact that, in turn, was overlain by a fining-upward sequence of fine-grained sandstone, siltstone, and stigmarian-rooted claystone. Coal occurs above the rooted claystone that then is overlain by a coarsening-upward sequence of claystone, siltstone, and fine-grained sandstone. Freshwater limestones identified in classical midcontinent Illinois cyclothems are not identified in the Silesian Basin (Fig. 4A). Fossil-plant assemblages are common components within the coarsening-upward sequences above coals. An upper erosional contact either ends the terrestrial cycle or removes much of the coarsening-upward sequence by subsequent landscape degradation. Dopita and Havlena (1980) circumscribed an ideal cycle consisting of a basal sandstone or kaolinite-rich clay overlain by mudrock or heterolithic, laminated lithologies that fined upward into a rooted seat earth over which there is coal. The top of their terrestrial cycle consists of massive mudstone or siltstone in which plant fossils and a freshwater fauna (e.g., *Carbonicola*; see Dopita and Kumpera, 1993) are preserved. These lithologies may be overlain by linguloid-bearing mudrock or fine clastics with open marine invertebrate fossils. Havlena (1986) noted that complete terrestrial cycles were less common than incomplete cycles in the succession. Marine cycles consist of fining-upward sequences of fine-grained sandstone to claystone in which macrofaunal elements are preserved in addition to occasional megafloral remains. The principal marine cycles have been attributed to eustatic mechanisms (e.g., Skoček, 1991; and others).



	STAGE	Regional Substage	Substage	Goniatite Zone		Members	Major Marine Intervals (Bands)
MISSISSIPPIAN	Serpukhovian	Namurian A	Arnsbergian	E2b	OSTRAVA Fm.	Poruba	XXVII Gaebler
				E2a		Jaklovec	XXI Barbora XVII Šusta
			Pendleian	E1		Hrušov Upper	XVI Enna
						Hrušov Lower	XII Františka
						Petřkovice	IX Naneta IV Leonard

FIGURE 3—Generalized stratigraphy of the Ostrava Formation, goniatite zones, and the major, basinwide marine zones (IV, Leonard; IX, Naneta; XII, Františka; XVI, Enna; XVII, Šusta; XXI, Barbora; and XXVII, Gaebler) within and separating members. The Pendleian and Arnsbergian are substages of the Serpukhovian.

Since the introduction of sequence-stratigraphic concepts, approaches to defining bounding surfaces of Carboniferous cyclothems have been refined (e.g., Gastaldo et al., 1993b; Heckel et al., 1998). Second-order sequences with durations ranging between 3–50 myr (Catuneanu, 2006) have been used to correlate strata across Gondwana, western and eastern Europe, and North America (Izart et al., 2002), while the recognition of third-order (0.05–3 myr; Catuneanu, 2006) and fourth-order cycles has advanced understanding at the basinal scale. Fourier and spectral analyses of fourth-order high frequency sequences have demonstrated periodicities that correspond to Milankovitch eccentricity (100 kyr and 400 kyr) cycles (Maynard and Leeder, 1992; Izart et al., 2002).

Cyclothem Model Used in the Present Study

The present investigation employs the cyclothem model proposed by Gastaldo et al. (1993b) to distinguish fourth-order (eccentricity) cycles within a sequence-stratigraphic framework (Fig. 4B). This model was developed within a coeval foreland basin, the Black Warrior Basin, Alabama, United States, and has been applied successfully by subsequent workers in that setting (e.g., Pashin, 1994, 2004). Autocyclic and allocyclic processes responsible for variation within cycles have been documented (Demko and Gastaldo, 1992, 1996), as well as constraints on the rapid generation of accommodation space in the system. Such rapid generation of accommodation results in the aerially restricted emplacement of tidal and nearshore-marine sediments above mire accumulations (Demko and Gastaldo, 1996; Gastaldo et al., 2004a). Such localized estuarine or nearshore deposits do not constitute transgression of the extensive coastal plain and can be distinguished by the presence of a

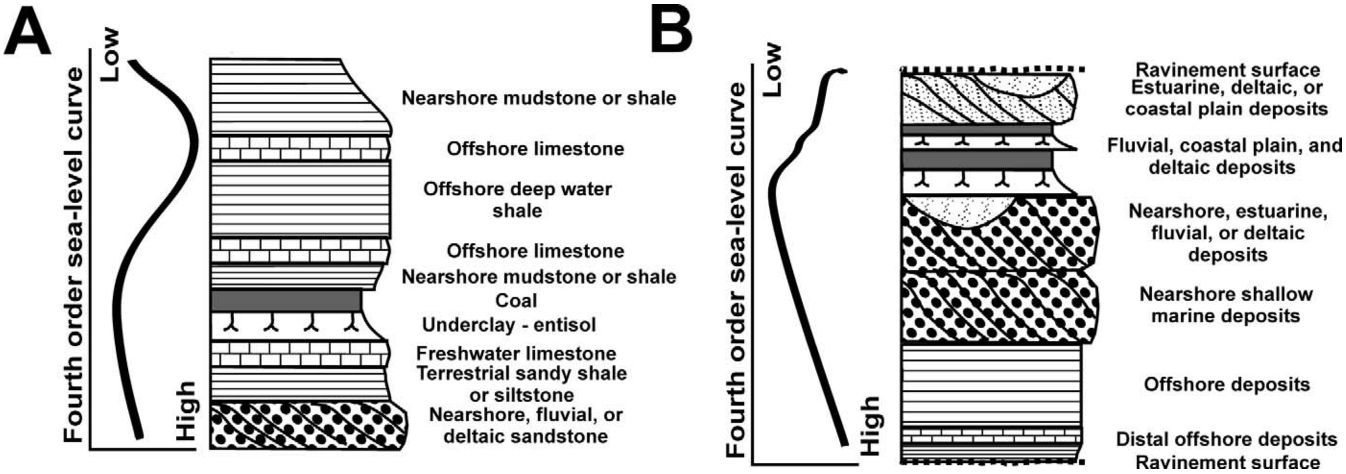


FIGURE 4—Comparison of traditional cyclothem model and sea-level curve with that used in the present study to define genetic cycles. A) Cyclothem stratigraphy as proposed by Wanless and Weller (1932), with peat-accumulating terrestrial environments located in the middle of the sequence. Note the required changes in relative sea level required by the model. B) Cyclothem (genetic-cycle) model used in this study (Gastaldo et al., 1993a and 1993b), in which the lower and upper bounding surfaces are the result of transgression and ravinement (dotted erosional contact). See text for details.

Lingula-dominated fauna (Gibson, 1990). The criteria established in the Black Warrior foreland basin, and applied in other basinal settings (Yang, 2007), have allowed for the application of the generalized model to the Ostrava-Karviná coalfield.

Liu and Gastaldo (1992) identified a regionally extensive, transgressive erosional surface in the Black Warrior Basin that marks the base of each transgressive systems tract (Pashin, 1994, 2004). This ravinement surface overlies either subaerially exposed soils (Histosols and Inceptisols) or coastal deposits that include tidalites and erect, *in situ* forests preserved as the result of coseismic activity (Gastaldo et al., 2004a). Well-preserved, open-marine megafaunal elements are entombed immediately above the transgressive erosional surface (maximum flooding surface) within a condensed section that may be variously bioturbated depending upon the sediment character (Gibson, 1990; Liu and Gastaldo, 1992). Each condensed bed can be identified petrophysically by a gamma spike in the electric-log signature (Pashin, 1994), allowing for its stratigraphic identification even in the absence of preserved invertebrate faunal elements. Fine clastic deposits, mainly siltstone, tens of meters in thickness, in which isolated and dispersed megafloral and megafaunal elements may be preserved, overlie the condensed bed. These deposits mark the progradational parasequences of the highstand systems tract. Pedogenic alteration of the last deposited marine sediments indicates subaerial exposure and sea-level drop during the lowstand systems tract, with subsequent fluvial, clastic-swamp (Gastaldo, 1987), and peat-mire deposits a function of variations in tectonic subsidence and local transgression (Demko and Gastaldo, 1992, 1996). Hence, coastal plain landscapes that include clastic-swamp deposits and peat mire accumulations are part of either a lowstand or transgressive systems tract (e.g., Falcon-Lang, 2004), depending upon their spatial arrangement within the basin.

MATERIALS AND METHODS

Stratigraphic Subdivision of Genetic Cyclothems

A composite stratigraphic section of the Ostrava Formation, originally developed in consort with mining activities and applied within the coalfield, was used first to identify continental coal-bearing intervals and marine coal-barren intervals. Names of coals and prominent marine zones, used for regional correlation purposes, were retained in this study and follow Řehoř and Řehořova (1972) and Dopita et al. (1997). This stratigraphic subdivision has been followed by all subsequent workers (e.g., Pešek et al., 1998). There was no one-to-one correlation found between designated coals or marine horizons and discrete cyclothems as modeled above. Rather, individual cyclothems consist of one or more discrete named coals and marine bands and vary in their thickness and sedimentological character depending upon geographic position in the basin (e.g., Fig. 5) .

The base of each genetic cycle circumscribed in this study begins with a transgressive erosional surface that overlies continental deposits (see Hampson et al., 1997, 1999, for discussions on alternatives to this application). This surface was identified in drawn stratigraphic logs as the contact between coal or roof shales and overlying open-marine or estuarine deposits in which megafaunal elements are preserved. A thick interval of fine-grained siliciclastics, in which marine invertebrates may be preserved, represents offshore-to-nearshore deposits that coarsen upward to coarse-to-medium-grained sandstone. Coarse, conglomeratic clastics have been interpreted as fluvial braidplain deposits in the Upper Silesian Basin (Havlena, 1977, and workers thereafter), marking the onset of terrestrialization, whereas thick sandstone has been ascribed to fluvial channel deposits (e.g., Pešek et al., 1998). Leached immature-to-mature paleosols with stigmarian horizons occur above and between fluvial sediments, with paludification of Entisols resulting in peat accumulation (Gastaldo and Staub, 1995). Thick peat deposits (economic coals) occur across the basin, although many contain siliciclastic partings and tonsteins (Dopita and Kumpera, 1993). Additionally, there are many thinner, regionally restricted coals that alternate with siltstone or mudstone deposits in which plant-fossil assemblages are well preserved (see Gastaldo et al., 2004a; DiMichele and Gastaldo, 2008; Gastaldo and Demko, 2009, for model of plant preservation in terrestrial sequences). Named major and minor coals within any genetic sequence, along with the plant-fossil assemblages therein, were placed together if they occurred below the bounding (erosional) surface (e.g., Fig. 5, Koks and Heřman cycle). These continental deposits represent the result of coastal plain aggradational and degradational processes, which are dependent on allocyclic mechanisms (Demko and Gastaldo, 1996; Gastaldo and Demko, 2009).

The exact cause for the development of accommodation for terrestrial deposits is an interplay between tectonism and eustasy (Klein and Willard, 1989; Klein, 1990). Tectonic accommodation in coastal-plain regimes is regional and can be identified by the preservation of *in situ* erect forests and autochthonous assemblages either directly above peat mires or in clastic swamps (Gastaldo et al., 2004a, 2004b). In contrast, accommodation generated by eustatic sea-level rise is not restricted geographically but can be traced across the basin. It is reflected by the development of thick, extensive marine intervals that can be correlated using petrophysical methods (gamma-ray spectrometry; see O'Mara and Turner, 1997) in the absence of preserved macroinvertebrates (Gastaldo et al.,

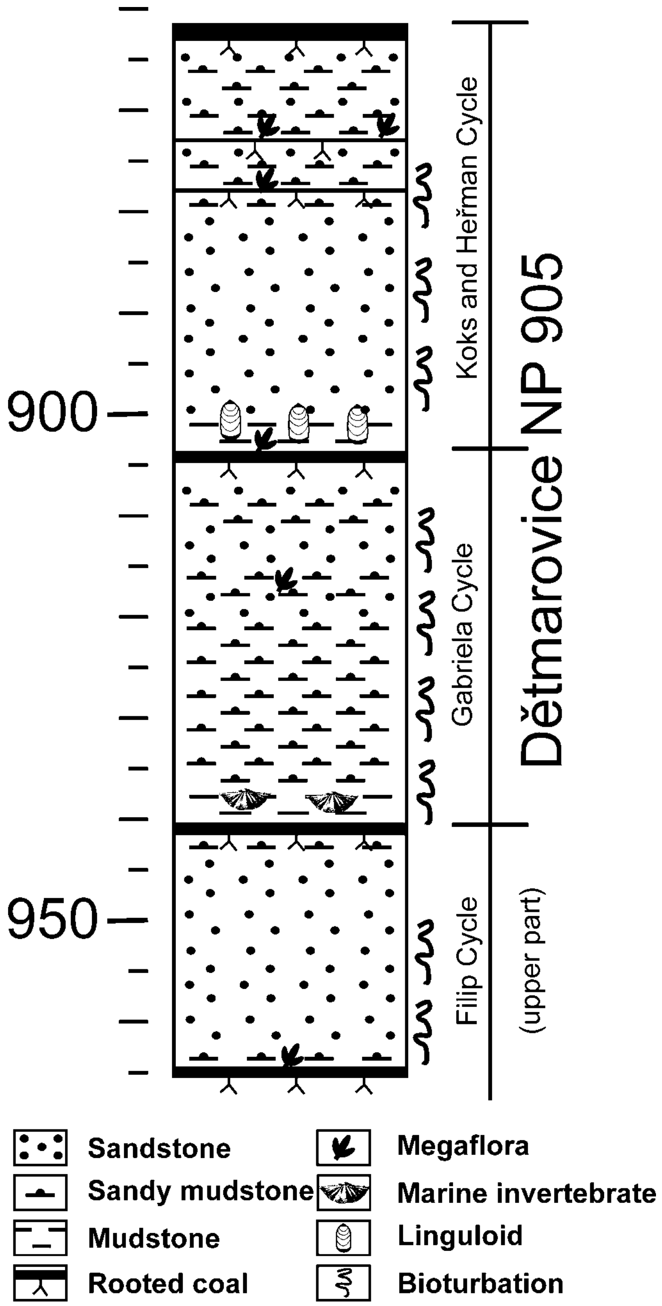


FIGURE 5—Stratigraphic log of the Dětmarovice NP 905 borehole, Ostrava-Hrabová, on which the Filip, Gabriela, and Koks and Heřman cycles are identified using the criteria of the present study. Scale in meters.

2009). A basin model for the Ostrava-Karviná Basin similar to that recently proposed by Waksmundzka (2007) for the Lublin basin in Poland does not exist. Hence, variation in thickness of any individually identified cycle in any one of the mining districts could not be interpreted as differences in localized tectonic-induced subsidence, erosional loss in response to differences in the angle of ravinement across the coastal plain (see Liu and Gastaldo, 1992), or degradation of the area by valley incision during lowstand. Regardless, each succession of continental deposition indicates a period of time without the basinwide incursion or interplay of marine conditions. Once marine conditions are evident in the stratigraphy above a transgressive erosional surface, a new cycle is defined. The name of each cyclothem is based on the most important economic coal occurring between bounding surfaces and follows conventional assignment in the basin.

Based upon the composite section, analyses of drill-core reports, and infrequent petrophysical logs, 54 genetic cycles are identified in the Ostrava Formation (Table 1). This approach differs from previous estimates based on Řehoř and Řehořova's (1972) work that identified 80 marine zones arranged into 21 marine groups. Within these marine groups are several principal, thick marine intervals that occur basinwide and include the Leonard (IV), Naneta (IX), Františka (XII), Enna (XVI), Šusta (XVII), Barbora (XXI), and Gaebler (XXVII; see Fig. 3). Several of these consist of multiple, stacked marine zones ascribed to the interval (e.g., Enna, Barbora; see Gastaldo et al., 2009).

Megafloral Paleobotany

The megaflora of the Ostrava-Karviná coalfield is well known and based on detailed studies conducted by several workers including Patteisky (1930, 1957), Havlena (1960, 1971), and Purkyňová (1963, 1970a, 1970b, 1977, 1983). Systematic identification of all megafloral elements encountered during the drilling program was done by Purkyňová and documented within each of more than 1000 drill-core reports. Drill-core diameter ranged from 3 cm to 10 cm. Paleobotanical investigations were made following stratigraphic, sedimentologic, and sample removal for coal petrographic analyses. This resulted in centimeter-scale stratigraphic resolution of megafloral elements within recognized and correlated coal-and-marine intervals. There is only a 2-year hiatus in Purkyňová's analyses; hence, a single researcher is responsible for systematic identification to species, where possible, for nearly all fossil plant material in the basin.

Paleobotanical, stratigraphical, and sedimentological data from >265 drill-core reports, housed in the Silesian Museum, Opava, Czech Republic, were compiled for this analysis and include both Flöznahe assemblages (lycopsid- and sphenopsid-dominated assemblages associated with peat-mire accumulations) and Flözferne assemblages (extrabasinal, pteridosperm and fern-dominated assemblages preserved between coals; see Havlena, 1961, 1971). Type specimens and representative hand samples were examined at the Regional Silesian Museum, Opava, and the Ostrava Museum, Ostrava, Czech Republic, whereas representative drill core was provided for examination by the Důl Paskov mine, Paskov, Czech Republic. A data set of 18,910 fossil plants was obtained from these 265 core reports (23% of available reports), and each taxon was assigned to its respective cyclothem (see below). Because all data originate exclusively from drill core, only presence-absence of a taxon at a specific stratigraphic horizon (cycle) was recorded. Nonetheless, autochthonous and parautochthonous assemblages (Gastaldo et al., 1995) found in close proximity to coals can be separated from allochthonous assemblages preserved in fluvial and marine deposits. Hence, in the broadest sense, it is possible to compare isotaphonomic assemblages (those preserved under the same conditions *sensu* Behrensmeyer et al., 2000) from cyclothem to cyclothem. Each stratigraphically bound assemblage represents a sampling of the vegetation that grew on the coastal plain during that specific time interval under the same long-term conditions (DiMichele and Gastaldo, 2008).

Ninety six percent of all recognized taxa within the coalfield occur in the data set. Of reported taxa, 77% were found within drill-core reports. These were supplemented by an additional 19% (endemic) taxa that were added from the literature and may represent single occurrences. In total, 172 megafloral elements are identified from the Ostrava-Karviná coalfield, 154 of which are found in the Ostrava Formation and Prokop Seam of the Karviná Formation (see the Supplementary Data[1]).

U-Pb Geochronology

Tonstein samples from the Ludmila (Petřkovice Member; coal 043 of Dopita et al., 1997) and Karel (Hrušov Member; coal 106 of Dopita et al., 1997) coals were obtained from the Stařič 2 drill core recovered at

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[1] www.paleo.ku.edu/palaios

TABLE 1—Genetic cycles identified in the Ostrava and lowermost Karvina Formations, Upper Silesian Basin, Czech Republic, based on a composite section. Cycles are placed within members of each formation according to Dopita and Kumpera (1993). Groups identified using unweighted pair group method with arithmetic mean (UPGMA) clustering are marked in the Cluster column (see Fig. 7). The number of identified taxa in each cycle is reported in the α-diversity column. Results from Bayesian statistical analysis using AutoClass C are identified in the Class column along with the probability (p) of the case clustering within the class (see Fig. 7).

Cluster	Case (Cycle)	Member	Class	α-diversity
1	1 Stur	Petřkovice	0; p = 1.0	27
	2 Štolní	Petřkovice	0; p = 1.0	27
	3 Teodor	Petřkovice	0; p = 1.0	33
	4 Fany	Petřkovice	0; p = 1.0	36
	5 Novodvorská	Petřkovice	0; p = 1.0	37
2a	6 Leonard	Petřkovice	0; p = 1.0	40
	7 Max	Petřkovice	0; p = 1.0	43
	8 Ludmila	Petřkovice	0; p = 1.0	43
	9 Terezie	Petřkovice	0; p = 1.0	43
	10 Bonhumila	Petřkovice	0; p = 1.0	46
	11 Viléma	Petřkovice	0; p = 1.0	49
	12 Fridolín	Petřkovice	0; p = 1.0	49
	13 Daniel	Petřkovice	0; p = 1.0	48
	14 Cyprián	Petřkovice	0; p = 1.0	48
2b	15 Bruno	Petřkovice	0; p = 1.0	52
	16 Pavel	Petřkovice	0; p = 1.0	51
	17 Naneta	Petřkovice	0; p = 1.0	54
	18 Brousek	Petřkovice	0; p = 1.0	54
	19 Karel	Hrušov	0; p = 1.0	55
	20 Růžena	Hrušov	0; p = 1.0	57
3a	21 Pavla	Hrušov	2; p = 1.0	49
	22 Petr	Hrušov	2; p = 1.0	49
	23 Olympie	Hrušov	2; p = 1.0	49
	24 Olga	Hrušov	2; p = 1.0	49
	25 Minerva	Hrušov	2; p = 1.0	49
	26 Gisela	Hrušov	2; p = 1.0	49
	27 Františka	Hrušov	2; p = 1.0	50
	28 Vaclav	Hrušov	2; p = 1.0	49
	29 Tea	Hrušov	2; p = 1.0	48
	30 Roland	Hrušov	2; p = 1.0	48
	31 Pipin	Hrušov	2; p = 1.0	47
	32 Osmana	Hrušov	2; p = 1.0	48
	33 Natálie	Hrušov	2; p = 1.0	46
	34 Makra	Hrušov	2; p = 1.0	48
3b	35 Flora	Hrušov	2; p = 1.0	44
	36 Enna	Hrušov	2; p = 1.0	46
4a	37 Šusta	Jaklovec	1; p = 1.0	40
	38 Hugo	Jaklovec	1; p = 1.0	41
	39 Eleonora	Jaklovec	1; p = 1.0	38
	40 Gabriela	Jaklovec	1; p = 1.0	38
	41 Minerva	Jaklovec	1; p = 1.0	37
	42 Uranie	Jaklovec	1; p = 1.0	37
	43 Emil	Jaklovec	1; p = 1.0	37
	44 Barbora	Jaklovec	1; p = 1.0	39
4b	45 Filip-Gustav	Poruba	1; p = 1.0	39
	46 Gabriela	Poruba	1; p = 1.0	42
	47 Koks-Heřman	Poruba	1; p = 1.0	42
	48 Jindřich	Poruba	1; p = 1.0	42
	49 Justín	Poruba	1; p = 1.0	43
	50 Konrád	Poruba	1; p = 1.0	43
	51 Lotar	Poruba	1; p = 1.0	44
	52 Max	Poruba	1; p = 1.0	42
	53 Otokar	Poruba	1; p = 1.0	43
	54 Gaebler	Poruba	1; p = 1.0	38
	55 Prokop Coal	Saddle	3; p = 1.0	58

the Důl Paskov mine. Single crystal zircons were recovered from each tonstein and subjected to a modified version of the chemical abrasion method of Mattinson (2005). Zircon separates were placed in a muffle furnace (900°C, 60 hours) in quartz beakers. Single crystals were transferred to 3-ml Teflon PFA beakers, rinsed twice with 3.5 M HNO_3, and loaded into 300-ml PFA microcapsules. Fifteen microcapsules were placed in a large-capacity Parr vessel, and the crystals were partially dissolved in 120 ml of 29 M HF with a trace of 3.5 M HNO_3 (10–12 hours at 180°C). The contents of each microcapsule were returned to 3-ml PFA beakers, the HF removed, and the residual grains rinsed in ultrapure H_2O, immersed in 3.5 M HNO_3. They were then ultrasonically cleaned for an hour and fluxed on a hotplate (80°C) for an hour. The HNO_3 was removed, and the grains again were rinsed in ultrapure H_2O or 3.5M HNO_3 before being reloaded into the same 300-ml Teflon PFA microcapsules (rinsed and fluxed in 6 M HCl during crystal sonication and washing) and spiked with the EARTHTIME mixed ^{233}U-^{235}U-^{205}Pb tracer solution (ET535). These chemically abraded grains were dissolved in Parr vessels in 120 ml of 29 M HF with a trace of 3.5 M HNO_3 (220°C for 48 hours), dried to fluorides, and then redissolved in 6 M HCl at 180°C overnight. Uranium and Pb were separated from the zircon matrix using an HCl-based, anion-exchange chromatographic procedure (Krogh, 1973), eluted together, and dried with 2 μl of 0.05 NH_3PO_4.

Lead and uranium were loaded on a single outgassed Re filament in 2 μl of a silica-gel–phosphoric acid mixture (Gerstenberger and Haase, 1997), and U and Pb isotopic measurements made on a GV Isoprobe-T multicollector thermal ionization mass spectrometer equipped with an ion-counting Daly detector. Lead isotopes were measured by peak jumping all isotopes on the Daly detector for 100–150 cycles, and corrected for 0.22% ± 0.04% per atomic mass unit (amu) mass fractionation. Transitory isobaric interferences due to high molecular-weight organics, particularly on ^{204}Pb and ^{207}Pb, disappeared within $\sim$30 cycles, while ionization efficiency averaged 10^4 cps·pg^{-1} of each Pb isotope. Linearity (to $\geq 1.4 \times 10^6$ cps) and the associated dead time correction of the Daly detector were monitored by repeated analyses of standard NBS-982 and have been constant since installation. Uranium was analyzed as UO_2^+ ions in static Faraday mode on 10^{11} ohm resistors for 150–200 cycles and corrected for isobaric interference of $^{233}U^{18}O^{16}O$ on $^{235}U^{16}O^{16}O$ with an ^{18}O:^{16}O of 0.00205. Ionization efficiency averaged 20 mV·ng^{-1} of each U isotope. U mass fractionation was corrected using the known ^{233}U:^{235}U ratio of the ET535 tracer solution.

U-Pb dates and uncertainties were calculated using the algorithms of Schmitz and Schoene (2007) and a ^{235}U:^{205}Pb ratio for ET535 of 100.18 ± 0.05. ^{206}Pb:^{238}U ratios and dates were corrected for initial ^{230}Th disequilibrium using a Th:U[magma] of 3 ± 1 using the algorithms of Crowley et al. (2007), resulting in a systematic increase in the ^{206}Pb:^{238}U dates of $\sim$90 kyr. Common Pb in analyses $<$1 pg was attributed to laboratory blank and subtracted based on the measured laboratory Pb isotopic composition and associated uncertainty. This simple correction is typical of most analyses. Occasional analyses with common Pb $>$1 pg were assumed to contain initial Pb within mineral inclusions, which was subtracted based on the model two-stage Pb isotope evolution of Stacey and Kramers (1975). Uranium blanks are difficult to precisely measure but are $<$0.1 pg. Over the course of the experiment, isotopic analyses of the TEMORA zircon standard yielded a weighted mean ^{206}Pb:^{238}U age of 417.43 ± 0.06 ($n = 11$, mean square weighted deviate $= 0.8$).

Multivariate Methods

Taxonomic presence-absence data for individual cycles were compiled into a spreadsheet based on 265 drill-core reports. Taxa identified to species (235) include lycopsid stems (27), leaves (2), strobili (3), rhizomorphs (2), and ground-cover taxa (i.e., *Eleutherophyllum*; 2); sphenopsid stems (15), leaves (9), and ground-cover or liana taxa (i.e., *Sphenophyllum*; 8); filicopsid leaves (13); pteridosperm leaves (61); taxa that

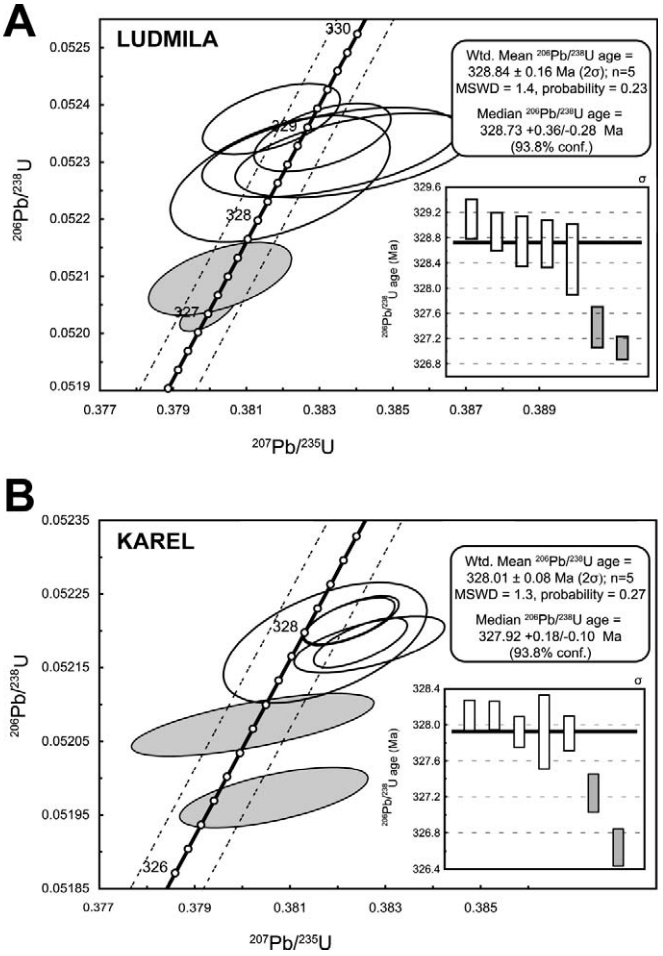

FIGURE 6—Concordia diagrams for zircons recovered from tonstein samples in the A) Ludmila coal (Petřkovice Member) and B) Karel coal (Hrušov Member). MSWD = mean square weighted deviate.

may be either pteridosperms or filicopsids (e.g., *Sphenopteridium*, *Rhodeopteridium*, *Diplotmema*; 84, most of which are probably pteridosperm, based on frond architecture), and other gymnosperms (e.g., *Cordaites*, *Ginkgophyton*, *Dicranophyllum*; 5). Pteridophyte and pteridosperm sterile-leaf taxa were used in the analysis to avoid duplication of natural biological species in these groups. Open cells that occurred between the first and last appearance datums of a taxon were converted to presence data to complete each biostratigraphic range within the basin (i.e., range-through data were used). It was assumed, and confirmed by Purkyňová, that many of these taxa were found in other drill cores within the specific coal cycle where no record existed in the subset of reports. No analyses were conducted to assess the potential influence of the Signor-Lipps effect (Signor and Lipps, 1982).

Taphonomic Considerations for Justifying Range-Through Data.—The potential for preservation of plant parts in coastal wetland environments is restricted to a very short temporal window, and this is particularly true in the tropics (Gastaldo and Staub, 1999). Preservation of plant-fossil assemblages is predicated on litter being entombed and maintained under specific geological and geochemical conditions over the short-to-long term (DiMichele and Gastaldo, 2008; Gastaldo and Demko, 2009). These conditions can be satisfied only under a few constrained settings and processes in coastal plain, peat-accumulating, and clastic regimes (Gastaldo et al., 1995; Gastaldo et al., 2004a). Additionally, the spatial extent over which preservation occurs within any particular landscape is restricted. Hence, there is a limited patchwork of sites available for plant-part accumulation and potential preservation at any point in time within various landscapes (peat-accumulating or siliciclastic depositional environments) that are encompassed within a cyclothem.

Plants (or parts thereof) that are preserved as fossils generally are the dominant taxa in the landscape (Gastaldo et al., 1987; Burnham et al., 1992; Gastaldo, 1994). Populations of any such taxon must be large enough to contribute sufficient biomass across space and time to be represented in the stratigraphic record. It has been demonstrated that significant vegetational heterogeneity existed in the Carboniferous lowlands (Gastaldo, 1987; Gastaldo et al., 2004b; DiMichele et al., 2007), with a mosaic of taxa occurring within both peat-accumulating (Histosol) and siliciclastic (Inceptisol, Entisol, Gleysol) soils. Some taxa are reported from both regimes, while others may be restricted to one soil type or another. It is envisioned that these broad soil categories coexisted within the coastal zone at any point in time, similar to the contemporaneous peat and nonpeat accumulating regimes found throughout southeast Asia today (e.g., Gastaldo et al., 1993a; Staub and Gastaldo, 2003).

The presence of a taxon in one genetic cycle of this compiled data set, its absence in the overlying cycle, and reappearance in subsequently higher cycles implies that it existed in sufficiently large populations, growing in a Histosol, Gleysol, or both, to be preserved at any point when conditions were met for inclusion in the plant-fossil record. With the cycle duration identified in this study (see below), extirpation of such populations from the basin across one cycle boundary and their subsequent recolonization or reinvasion at a later time under the same physical growth and climatic conditions would require unique circumstances that removed them entirely from the landscape (e.g., fungal blight). In contrast, it is parsimonious to believe that populations of these taxa existed somewhere at some time within the landscape where no record exists in the subsample of drill-core reports. This assumption has been made and applied to the range-through data used in the following analyses.

Statistical Analyses

Form taxa for vegetative and reproductive structures identifiable only at the generic level (e.g., sphenopsid cones, pteridosperm seeds, and pollen organs) and singletons (only one occurrence in the data set; e.g., *Dichophyllites nemejcii*, *Ginkgophyton delvalii*) were omitted, resulting in a data set of 121 taxa (Ostrava and Karviná Formations), of which 28 taxa are known exclusively from the Karviná Formation (see the Supplementary Data[1]).

Similarity matrices were calculated for the data set using simple matching, Sorenson, and Jaccard association coefficients and then subjected to constrained and unconstrained unweighted pair group method with arithmetic mean cluster analyses using MVSP, ver. 3.1 (Kovach, 2006). The data set used for these analyses included all Ostrava Formation taxa meeting the criteria outlined above and those present in the overlying Prokop Coal Seam of Pennsylvanian age (see the Supplementary Data[1]).

Cluster analysis using Bayesian classification was conducted with AutoClass C, ver. 3.3.5 (http://ti.arc.nasa.gov/project/autoclass/autoclass-c/; Hanson et al., 1991; Cheeseman and Stutz, 1996). The same data set used in the cluster analysis was analyzed with the exception that taxa ranging throughout the Ostrava and lowermost Karviná Formations (e.g., *Pecopteris aspera*; see the Supplementary Data[1]) were omitted because these attributes have no influence on the identification of classes. Cluster 0 is identified by AutoClass C as the first stable configuration; cluster 1 is the second stable configuration; and so forth. The single multinomial model was employed because the data are discrete, and data were subjected to 1000 runs to exhaust possible duplicate classifications.

RESULTS

U-Pb Geochronology

Seven single zircon grains analyzed from the Ludmila coal tonstein yielded precise and concordant results with ^{206}Pb:^{38}U dates ranging from 327.0 Ma to 329.1 Ma (Fig. 6A; Table 2). Two of the crystals yielded

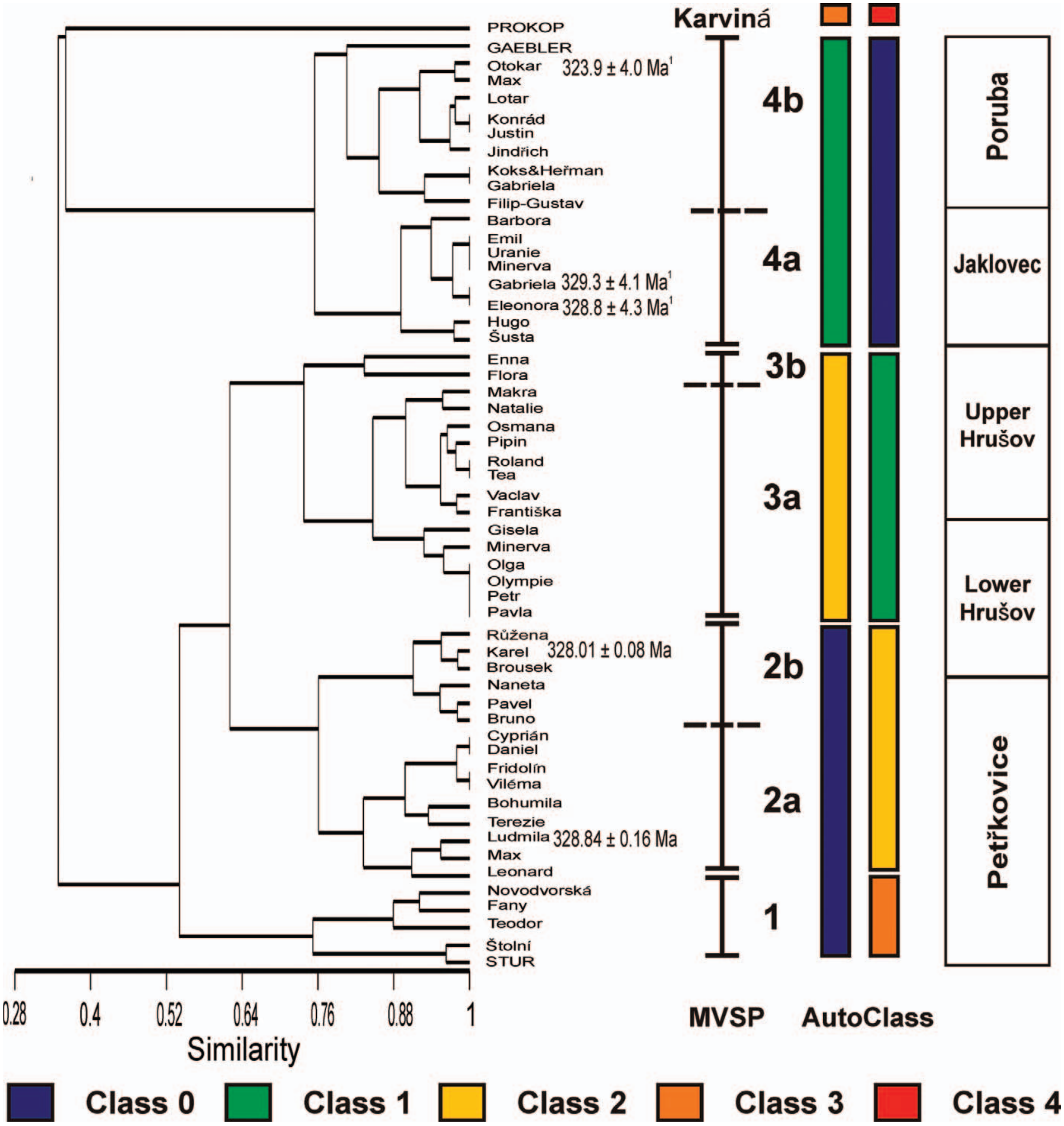

FIGURE 7—Dendrogram plot of the Ostrava Formation macrofloral assemblages in named genetic cycles following constrained cluster analysis using unweighted pair group method with arithmetic mean in MVSP, ver. 3.1 (Kovach, 2006). The results of the four- and five-class solutions using Bayesian classification and the AutoClass C program (Cheeseman and Stutz, 1996) are shown in colored bars and are congruent with clustering results. The Prokop coal is the lowest genetic cycle in the Karvina Formation (Pennsylvanian). Four main MVSP clusters are identified (1–4) in the Mississippian, in which subclusters can be recognized (e.g., 2a, 2b) using either the Jaccard or Sorenson coefficient; results are shown for the Jaccard coefficient. Scale in percentage of similarity between macrofloral assemblages. Geochronometric dates for the Ludmila and Karel-coal tonsteins are from the present study; [1]dates are recalibrations of the Hess and Lippolt (1986) estimates. See text for details.

substantially younger dates of 327.0 and 327.4 Ma and are interpreted as affected by residual Pb-loss despite aggressive chemical abrasion. The remaining five of the seven crystals produced a concordant and equivalent cluster of dates with a weighted mean ^{206}Pb:^{238}U age of 328.84±0.16 Ma (2 sigma, mean square weighted deviate = 1.4). Alternatively, the robust median ^{206}Pb:^{238}U age of the five crystals is 328.73+0.36/–0.28 Ma at the 95% confidence interval. Given the acceptable probability of fit, the former age and error are interpreted as representative of the time of tonstein emplacement. It may be noted that the quoted age uncertainty includes analytical uncertainties such as counting statistics, spike subtraction, and blank and initial common Pb subtraction and is appropriate when comparison is made to other ^{206}Pb:^{238}U ages obtained with the EARTHTIME spike or when those spikes are cross calibrated with the EARTHTIME gravimetic standards. If used in comparison with ages

TABLE 2—U-Th-Pb isotopic data for the Ludmila and Karel tonsteins recovered from the Stařič 2 borehole, Důl Paskov, Czech Republic. (a) z1, z2, etc. = single zircon grains annealed and chemically abraded after Mattinson (2005). Bold analyses included in age calculations. (b) Model Th:U ratio calculated from radiogenic ^{208}Pb:^{206}Pb ratio and ^{206}Pb:^{238}U age. (c) Pb* and Pbc represent radiogenic and common Pb, respectively; mol% ^{206}Pb* with respect to radiogenic, blank, and initial common Pb. (d) Measured ratio corrected for spike and fractionation only. Mass fractionation correction of 0.22% ± 0.02% (1 sigma)·(atomic mass unit)$^{-1}$ was applied to all single-collector Daly analyses, based on analysis of NBS-981 and NBS-982. (e) Corrected for fractionation, spike, and common Pb; procedural blank estimated at 1% ± 25% (1 sigma) with a composition of ^{206}Pb:^{204}Pb = 18.60% ± 0.80% ^{207}Pb:^{204}Pb = 15.69% ± 0.32%; ^{208}Pb:^{204}Pb = 38.51% ± 0.74% (1 sigma). Excess common Pb assigned an initial composition based on the two-stage model of Stacey and Kramers (1975) at 0.33 Ma. (f) Errors are 2 sigma, propagated using the algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007). (g) Calculations are based on the decay constants of Jaffey et al. (1971). ^{206}Pb:^{238}U and ^{207}Pb:^{206}Pb ratios and ages corrected for initial disequilibrium in ^{230}Th:^{238}U using Th:U [magma] = 3.

		Compositional parameters						
Sample (a)	Th/U (b)	^{206}Pb* × 10^{-13} mol (c)	mol % ^{206}Pb* (c)	Pb*/Pbc (c)	Pbc/(pg) (c)	^{206}Pb/^{204}Pb (d)	^{208}Pb/^{206}Pb (e)	^{207}Pb/^{206}Pb (e)
Karel coal (103) tonstein, Hrusov Member, Ostrava Formation (ton. 106-B2 Karel, 146.92-146.94 meters, Stařič 2 borehole)								
z2	**0.425**	**1.7659**	**98.56%**	**20**	**2.13**	**1275**	**0.134**	**0.053099**
z1	**0.408**	**1.8636**	**99.06%**	**31**	**1.45**	**1975**	**0.129**	**0.053095**
z3	**0.277**	**2.0427**	**97.76%**	**12**	**3.87**	**817**	**0.088**	**0.053158**
z4	**0.340**	**0.7713**	**97.01%**	**9**	**1.97**	**614**	**0.107**	**0.053055**
z5	**0.348**	**1.0347**	**98.40%**	**18**	**1.39**	**1156**	**0.110**	**0.053186**
z7	0.510	0.6058	97.90%	14	1.07	884	0.161	0.052961
z6	0.401	0.7902	98.49%	19	1.00	1231	0.127	0.053123
Ludmila coal (043) tonstein, Petrkovice Member, Ostrava Formation								
z1	**0.478**	**0.8890**	**97.80%**	**13**	**1.65**	**837**	**0.151**	**0.052853**
z5	**0.426**	**0.5580**	**98.78%**	**24**	**0.57**	**1520**	**0.135**	**0.053079**
z4	**0.397**	**0.3594**	**97.65%**	**12**	**0.71**	**791**	**0.126**	**0.053134**
z3	**0.204**	**0.3942**	**97.77%**	**12**	**0.74**	**833**	**0.065**	**0.053234**
z7	**0.408**	**0.1780**	**97.93%**	**14**	**0.31**	**897**	**0.129**	**0.052993**
z9	0.429	0.4019	98.72%	23	0.43	1455	0.135	0.052945
z2	0.421	1.4837	99.53%	64	0.57	4000	0.133	0.052955

derived from other decay schemes (e.g., ^{40}Ar:^{39}Ar, ^{187}Re:^{187}Os), the uncertainty in the ^{238}U decay constant can be added in quadrature, resulting in a revised age uncertainty of 328.84±0.38 Ma.

Seven single zircon grains from the Karel coal tonstein also yielded precise and concordant results, with ^{206}Pb:^{238}U dates ranging from 326.6 Ma to 328.1 Ma (Fig. 6B). Two of the crystals yielded substantially younger dates of 326.6 and 327.2 Ma and are interpreted as affected by residual Pb-loss despite aggressive chemical abrasion. The remaining five of the seven crystals produced a concordant and equivalent cluster of dates with a weighted mean ^{206}Pb:^{238}U age of 328.01±0.08 Ma (2 sigma, mean square weighted deviate = 1.3). Alternatively, the robust median ^{206}Pb:^{238}U age of the five crystals is 327.92+0.18/–0.10 Ma at the 95% confidence interval. Given the acceptable probability of fit, the former age and error are interpreted as representative of the time of tonstein deposition. The uncertainty in the ^{238}U decay constant can be added in quadrature, resulting in a revised age uncertainty of 328.01±0.36 Ma.

Megafloral Paleobotany

The number of taxa per cyclothem ranges from 27 (above the Stur marine horizon) to 57 (Růžena cycle). Increases or decreases in the number of taxa that account for at least a 10% change in diversity occur between the Štolní and Teodor (+6 taxa), Růžena and Pavla (−8), Enna and Šusta (−6), Otokar and Gaebler (−5), and the Gaebler and Prokop (+20) cycles. These generally represent the appearance of new taxa rather than replacement, as systematic turnover and replacement occur elsewhere in the section (see below). The systematic diversity stabilizes above the Terezie cycle (upper Petřkovice Member) with an average diversity of 47 taxa per cycle. There is an increase in diversity per cycle between the Stur and Bruno within the lower part of the Ostrava Formation, as the thickness of the terrestrial coal-bearing interval becomes greater.

Cluster Analyses.—Similar dendrograms result from cluster analyses based on the calculated similarity coefficients, with differences in the number of cyclothems assigned per cluster. These occur because of the mathematical functions associated with the calculation of binary (dis)similarity coefficients. In the case of the simple-matching-coefficient dendrogram, similarity coefficients are calculated with the assumption that not only the presence but also the absence of a taxon is significant when two adjacent cycles are compared. Hence, the simple-matching coefficient assumes that there is an equal probability that all taxa identified in the Ostrava Formation occurred throughout the entire stratigraphic record, but this is not the case within the data set. For example, Visean forms (e.g., *Archaeocalamites scrobiculatus*) disappear low in the section, and new taxa (e.g., *Karinopteris laciniata* in the Enna; *Rhodeopteridium tenue* in the Filip-Gustav) appear at various higher stratigraphic levels. In addition, the high number of absent taxa in the Gaebler (Mississippian) cycle and overlying Prokop (Pennsylvanian) cycle result in a high similarity coefficient that is a data anomaly using the simple-matching coefficient. There is no underlying assumption with either Jaccard or Sorensen coefficients of an equal probability that all taxa in the stratigraphy could co-occur. Hence, first and last appearance datums have more influence on the similarity coefficients of adjacent cycle lists. Only the dendrogram from the Jaccard analysis is presented (Fig. 7) and discussed further; it is identical to that of the Sorensen coefficient dendrogram. Additionally, constrained and unconstrained data input resulted in the same cycle clustering.

Four major groups occur in the results of the cluster analysis, three of which can be subdivided into six subgroups of cyclothems (Fig. 7). Five cycles are aggregated at the base of the Ostrava Formation into the first cluster and are characterized by late Visean taxa (Kulm facies; see Purkyňová, 1977) that range into the Serpukhovian. Rare megafloral elements, such as *A. scrobiculatus*, are preserved in allochthonous (transported) assemblages that translate into low systematic diversities in these basal clusters (average α-diversity = 32 taxa). Hence, although more typical early Serpukhovian (Namurian A) taxa co-occur with the Visean elements, systematic diversity only begins to increase in the Fany cycle with the deposition of thicker transitional and continental deposits (cluster 2, Fig. 7; Table 1).

The second major cluster consists of 15 genetic cycles and subdivides into two units (Fig. 7), in which assemblages are bundled based on similarity coefficients >0.80. The stratigraphically lowest subcluster consists of 9 cycles with an average α-diversity of 45 taxa, whereas the uppermost subcluster consists of 6 cycles with an average α-diversity of 53. There

TABLE 2—Continued

Isotope ratios						Isotopic ages		
% err (f)	$^{207}\text{Pb}/^{235}\text{U}$ (e)	% err (f)	$^{206}\text{Pb}/^{238}\text{U}$ (e)	% err (f)	corr. coef.	$^{207}\text{Pb}/^{206}\text{Pb}$ (g) ± (f)	$^{207}\text{Pb}/^{235}\text{U}$ (g) ± (f)	$^{206}\text{Pb}/^{238}\text{U}$ (g) ± (f)
0.184	**0.382277**	**0.215**	**0.052214**	**0.052**	**0.672**	**333.1 ± 4.2**	**328.71 ± 0.60**	**328.10 ± 0.17**
0.175	**0.382245**	**0.203**	**0.052214**	**0.049**	**0.652**	**332.9 ± 4.0**	**328.69 ± 0.57**	**328.10 ± 0.16**
0.177	**0.382477**	**0.210**	**0.052184**	**0.053**	**0.702**	**335.5 ± 4.0**	**328.86 ± 0.59**	**327.92 ± 0.17**
0.404	**0.381736**	**0.457**	**0.052184**	**0.128**	**0.532**	**331.2 ± 9.2**	**328.31 ± 1.28**	**327.92 ± 0.41**
0.303	**0.382663**	**0.337**	**0.052182**	**0.060**	**0.627**	**336.7 ± 6.9**	**329.00 ± 0.95**	**327.90 ± 0.19**
0.500	0.380250	0.544	0.052073	0.067	0.692	327.1 ± 11.4	327.22 ± 1.52	327.24 ± 0.21
0.386	0.380693	0.423	0.051975	0.064	0.628	334.1 ± 8.7	327.55 ± 1.18	326.63 ± 0.20
0.358	**0.381680**	**0.402**	**0.052376**	**0.096**	**0.547**	**322.5 ± 8.1**	**328.27 ± 1.13**	**329.09 ± 0.31**
0.358	**0.383075**	**0.399**	**0.052343**	**0.093**	**0.535**	**332.2 ± 8.1**	**329.30 ± 1.12**	**328.89 ± 0.30**
0.690	**0.383278**	**0.745**	**0.052317**	**0.123**	**0.516**	**334.5 ± 15.6**	**329.45 ± 2.10**	**328.73 ± 0.39**
0.645	**0.383961**	**0.697**	**0.052312**	**0.116**	**0.514**	**338.8 ± 14.6**	**329.95 ± 1.96**	**328.70 ± 0.37**
0.576	**0.381922**	**0.642**	**0.052271**	**0.173**	**0.499**	**328.5 ± 13.1**	**328.45 ± 1.80**	**328.45 ± 0.55**
0.374	0.380303	0.419	0.052096	0.101	0.538	326.4 ± 8.5	327.26 ± 1.17	327.38 ± 0.32
0.135	0.379978	0.167	0.052041	0.057	0.668	326.9 ± 3.1	327.02 ± 0.47	327.04 ± 0.18

is notable increasing diversity throughout the lower subcluster (Table 1) with an 8% rise in α-diversity between the Cyprián and Bruno cycles. Taxonomic affinities of first appearance datums in the Bruno cycle include sphenopsids, sphenopterids, and cf. pteridosperms; one sphenophyte marks its last appearance datum in the Cyprian cycle.

The third main cluster is composed of 16 genetic cycles and subdivides into two units with these aggregates based on similarity coefficients of 0.76. Fourteen cycles are assigned to cluster 3a, and only two cycles, the Flora and Enna, constitute cluster 3b. The average α-diversity cluster in 3a is 49 taxa, which drops to 45 in cluster 3b. First appearance datums that characterize cluster 3 are found in the sphenopsids (e.g., *Calamites ramosus*) and sphenopterids, with last appearance datums in the lycopsids (*Lepidodendron volkmannianum*, *Eleutherophyllum mirabile*), sphenopterids, and pteridosperms (e.g., *Diplotmema patentissimum*, *Archaeopteridium tschermakii*, *Sphenopteridium dissectum*, *Alethopteris willierei*; see Supplementary Data[1]).

The last cluster consists of 18 genetic cycles subdivided into two subunits (4a = 8 cycles, 4b = 10 cycles), with similarity coefficients >0.77. This cluster differs significantly from previous clusters (Fig. 7) owing to the appearance of new forms. The average α-diversity in cluster 4a is 39 taxa, whereas an average of 42 taxa occurs in cluster 4b. First appearance datums characterizing cluster 4a include sphenopsids (e.g., *Mesocalamites cistiformis*), sphenopterids, and pteridosperms (e.g., *Neuropteris kosmannii*, *Lyginopteris porubensis*), with last appearance datums in the pteridophytes (e.g., *Alloiopteris quercifolia*), sphenopsids (*Sphenophyllum sublaurae*), and sphenopterids. As expected, the Pennsylvanian Prokop Seam clusters separately from the cycles of the Ostrava Formation, but the Gaebler cycle clusters independently of the remainder of the Poruba Member.

When the results are plotted against the stratigraphic subdivision of the Ostrava Formation, it is evident that clusters do not coincide with recognized member boundaries (Fig. 7). Most genetic cycles identified within the Petřkovice Member occur together in cluster 2 with the exceptions that (1) the low-diversity basal cycles (cluster 1) become outliers and (2) the three lowermost cycles of the overlying Hrušov Member—that is, the Brousek, Karel, and Růžena—cluster with the cycles of the Petřkovice Member. Cluster 3 circumscribes the Hrušov Member with the stratigraphic boundary between the Lower and Upper Hrušov Member traditionally placed at the top of the basinwide Františka marine zone (Havlena, 1977, 1982), although this subdivision has fallen into disuse. The base of the Jaklovec Member is defined by the basinwide, thick Enna marine zone, which coincides with cluster 3b. The boundary between the Jaklovec and Poruba Members is placed at the top of the Barbora marine zone (Havlena, 1977, 1982), and the clustered floral assemblages reflect this stratigraphic subdivision (Fig. 7). Cluster 4b includes the remainder of the cycles in the Poruba Member. The Prokop coal, which accumulated after the mid-Carboniferous stratigraphic break and is assigned to the Saddle Member of the Karviná Formation, is dissimilar systematically to the later elements of the Ostrava Formation, as can be seen by its low similarity coefficient. The Jaklovec and Poruba assemblages are also different from those in the Hrušov and Petřkovice Members.

In summary, four distinct Mississippian megafloral assemblages are identified using cluster analysis. Floras of the oldest strata (Petřkovice and Hrušov Members) differ from those of the younger strata (Jaklovec and Poruba Members). Within these older assemblages, cluster 1 corresponds to the lowermost portion of the Petřkovice Member where megafloral elements more characteristic of the Visean occur. Clusters 2 and 3 consist of taxa preserved within the Petřkovice and Hrušov Members. There is a strong break between the upper and lower Ostrava assemblages following the Enna marine zone, with the upper assemblages being most similar, even if weakly, to the Pennsylvanian samples found following the mid-Carboniferous boundary in the Prokop coal (Karviná Formation).

AutoClass C Classification.—The most statistically significant AutoClass C analyses resulted in the identification of either four or five classes in the data set. The best four-class solution first was found on iteration 26, whereas the first five-class solution was identified on iteration 585. These two solutions are coincident with the cycle groupings delimited using cluster analysis (Fig. 7; Table 1), and each group was classified with 100% probability. AutoClass C also identified the significant attributes (taxa) that are most influential in determining the cluster of a stratigraphic cycle interval. Table 3 shows the top 50 taxa that influenced clustering patterns in the AutoClass results.

TABLE 3—The 50 most influential attributes (taxa) identified in AutoClass C, and the term influence value (I) minus the estimated mean and standard deviation for attribute k (*k).

Attribute name (taxon)	I-*k
Alloiopteris essinghii	1
Pecopteris plumosa	1
Pecopteris schwerinii	1
Lyginopteris baumleri	1
Karinopteris acuta	1
Mariopteris muricata	1
Paripteris gigantea	1
Cardiopteridium waldenburgense	1
Diplotmema subgeniculatum	1
Sphenopteris gracilis	1
Eusphenopteris michaeliana	1
Sphenopteris schwerinii	1
Cordaites borassifolius	1
C. palmaeformis	1
C. principalis	1
Lepidodendron selaginoides	1
Sigillaria elegans	1
Sigillaria schlotheimii	1
Sigillaria transversalis	1
Mesocalamites carinatus	1
Annularia radiata	1
Annularia subradiata	1
Asterophyllites charaeformis	1
Asterophyllites gothanii	1
Asterophyllites longifolius	1
Alloiopteris goeppertii	0.995
Lyginopteris bermudensiformis	0.995
Sphenopteridium dissectum	0.995
Diplotmema helenkianum	0.995
Mesocalamites cistiformis	0.995
Neuropteris bohdanowiczii	0.916
Dichophyllites nemejcii	0.916
Sphenopteris foliata	0.870
Archaeopteridium dawsonii	0.870
Sphenopteridium bifidum	0.858
Calamites cistii	0.836
Lyginopteris bartoneii	0.833
Lyginopteris larischii	0.812
Lyginopteris dicksonioides	0.806
Diplotmema dissectum	0.799
Sphenophyllum sublaurae	0.793
Lyginopteris fragilis	0.789
Palmatopteris furcata	0.789
Neuropteris kosmannii	0.784
Eleutherophyllum mirabile	0.774
Bothrodendron minutifolium	0.744
Lepidodendron simile	0.742
Alethopteris tectensis	0.731
Karinopteris laciniata	0.731
Neuropteris reticulopteroides	0.731

DISCUSSION

The persistence of multispecies megafloral assemblages (e.g., DiMichele and Phillips, 1996; DiMichele et al., 1996, 2002; Pfefferkorn et al., 2000) and microfloral assemblages (Peppers, 1996) over several million years duration has been demonstrated for tropical peat-accumulating mires and transitional wetland deposits of the Pennsylvanian of the Illinois Basin. Wetland species were replaced by close relatives from the same families or genera, resulting in recurrent vegetational patterns during both the Middle and Late Pennsylvanian (Pfefferkorn et al., 2008). Pfefferkorn and Thomson (1982) and DiMichele and Phillips (1996) attribute a change in vegetational composition at the Middle-Late Pennsylvanian (Moscovian-Kasimovian) boundary to climate perturbation, resulting in the regional extinction of arborescent lycopsids and their replacement by arborescent ferns (Pfefferkorn et al., 2008; but see Wagner and Lyons, 1997). Such persistence patterns are replicated earlier in the tropics of the Late Mississippian (Serpukhovian) in the Upper Silesian Basin, and are unique to the latest Paleozoic.

U-Pb Geochronology, Cycle Duration, and the Serpukhovian

Few isotopic dates have been obtained from the numerous tonsteins throughout the Upper Silesian Basin, with the most recent dates published by Hess and Lippolt (1986) from ash beds in the Jaklovec and Poruba Members. They obtained two ^{40}Ar:^{39}Ar dates from sanidines taken from tonsteins within the Jaklovec Member, one from the Eleonora coal (COT335, 324.6±2.8 Ma, 2 sigma) and the overlying Gabriela coal (COT365, 324.8±2.4 Ma, 2 sigma). The Gabriela coal date has been used as the boundary between the Pendleian and Arnsbergian (Fig. 3; see Menning et al., 2006). The one date reported from the Poruba Member comes from the Otokar coal (COT479, 319.5±2.3 Ma, 2 sigma) that occurs just beneath the Gaebler horizon (mid-Carboniferous boundary). These dates were obtained by calibration against the P-207 muscovite standard (82.6±1.0 Ma) and the ^{40}K decay constant recommended by Steiger and Jager (1977). In the same experiment, the secondary standard MMHb-1 hornblende yielded an age of 519.2±5.0 Ma (2 sigma), which allows normalization of these ages to more recent standard and decay-constant recalibrations. In their comprehensive intercalibration study, Renne et al. (1998) recommend an apparent age of 523.1 Ma for MMHb-1, intercalibrated to an age of 28.02 Ma for Fish Canyon Tuff sanidine (FCT-San) and the ^{40}K decay constant of Steiger and Jager (1977). More recently, Kuiper et al. (2008) have compared single-crystal ^{40}Ar:^{39}Ar sanidine ages to an astronomically tuned timescale in Miocene strata of the western Mediterranean and, thus, derive a new estimate of the ^{40}K decay constant, expressed as an age for FCT-San of 28.201±0.046 Ma (2 sigma). This arguably represents the most accurate means of comparing ^{40}Ar:^{39}Ar and U-Pb radiometric ages. Recalibrating the results of Hess and Lippolt (1986) to this new FCT-San age through MMHb-1 results in the following revised ages and uncertainties (including systematic errors associated with irradiation standard and decay constant): Jaklovec Member, Eleonora coal (328.8±4.3 Ma), Gabriela coal (329.3±4.1 Ma); Poruba Member, Otokar coal (323.9±4.0 Ma).

The precise U-Pb zircon-based depositional ages for the Ludmila and Karel coals reported here provide a means to determine cycle duration in this part of the Serpukhovian in the Ostrava Formation. The duration of sedimentation over the intervening 11 cycles between these coals is 0.83±0.24 myr (Fig. 7), the uncertainty derived solely from analytical error in the radiometric ages, given that comparison is made between ages within the same decay scheme. Hence, the resulting estimated cycle duration ranges from 54 kyr to 107 kyr, which only overlaps at the 95% confidence interval with the short-period (100 kyr) eccentricity cycle among potential orbital (Milankovitch) forcing mechanisms. A modicum of support for short-period eccentricity forcing also comes from considering Hess and Lippolt's (1986) ^{40}Ar:^{39}Ar sanidine age for the Otokar coal tonstein. The duration of sediment accumulation over the 34 cycles between the Karel and Otokar coals is calculated as 4.1±4.4 myr, resulting in an average cycle duration of 120 kyr, albeit with large uncertainty. Thus, it appears that Late Mississippian cycles in the Upper Silesian Basin conform to periodicities coincident with Milankovitch eccentricity (100 ka), although further precise U-Pb zircon dating of additional tonsteins is warranted to confirm whether cyclicity in the Upper Silesian basin adheres to a constant tempo, or if cryptic cycles, represented exclusively by marine deposits, also exist (Gastaldo et al., 2009).

Present estimates for the duration of the Serpukhovian range from 6.5 myr (Menning et al., 2006) to 8 myr (Gradstein et al., 2004), and it is now clear that the stage is longer than presently envisioned. Menning et al. (2006) accepted an age for the base of the stage at somewhere approaching 325 Ma or less, having moved the estimate from 333 Ma as proposed by Harland et al. (1990). Gradstein et al. (2004) place the base of the Serpukhovian at 326 Ma. The high-resolution U-Pb date presented for the Ludmila coal (328.84±0.16 Ma), stratigraphically within the middle of the Petřkovice Member of the Ostrava Formation and above the base of the Serpukhovian in the Upper Silesian Basin (Fig. 7), indicates that both the estimates of Gradstein et al. (2004) and Menning et al. (2006) are too young. Extrapolation of cycle duration in this part of the section, where chronometric control now exists, places the base of the Serpukhovian near 330 (329.7) Ma. Additional zircon analyses from tonsteins in other parts of the basin now are being conducted, with a better constrained chronostratigraphy forthcoming. Higher-resolution chronometric control in this tonstein-rich sequence will help resolve the overall duration of the Serpukhovian and those of the fourth- and fifth-order sequences.

Vegetational Persistence

Four principal stratigraphic cyclothem groups exist in the Ostrava Formation, each separated from the overlying cluster by a maximum of only 62% similarity (Fig. 7). Major changes in floral assemblages and, hence, Mississippian coastal plain landscapes are identified across the Novodvorská-to-Leonard, Růžena-to-Pavel, and the Enna-to-Šusta cycles within the Ostrava Formation and at the mid-Carboniferous boundary (Gaebler-to-Prokop contact). Such changes are not coincident necessarily with traditional stratigraphic boundaries within the basin (Fig. 7). These discrepancies are a function of (1) the way in which cycles are defined in the present study (with the inclusion of the marine sequence in the overlying coal-bearing strata), and (2) the persistence of terrestrial taxa across boundaries established on changes in marine megafauna (Řehoř, 1977). Subdivisions within all groups identified using cluster analysis, except for the basalmost (cluster 1, Fig. 7), occur when the proportion of assemblage similarity drops to ≤76%. Hence, persistence of vegetational assemblages in the paleotropical lowlands of the Carboniferous was established at the onset of glacioeustasy in the Late Mississippian (Serpukhovian) and is not a phenomenon associated only with Late Carboniferous sequences.

The question arises as to the duration of regional assemblage composition prior to the mid-Carboniferous drawdown that marked maximum glacial buildup across Gondwana (Frakes et al., 1992). The three principal groupings identified using AutoClass C consist of 20, 16, and 18 cycles, respectively (Table 1); the basalmost group can be subdivided into intervals of 5 and 15 cycles (Fig. 7). Single crystal U-Pb zircon ages from tonsteins in the Ludmila coal (Petřkovice Member; 328.84±0.16 Ma) and Karel coal (Hrušov Member; 328.01±0.08 Ma) allow for calculation of cycle duration approaching 100 kyr in this part of the stratigraphy. Hence, vegetational persistence in this paleoequatorial region was retained with durations of at least 1.5–1.8 myr.

There is no doubt that persistence exists within wetland-ecosystem biodiversity of the Late Mississippian landscape, where replacement species seem to be derived from within coastal lowlands during times of background turnover. This pattern occurs in the Middle and Late Pennsylvanian (DiMichele and Phillips, 1996) as well as in the Permian of West Texas (W.A. DiMichele, personal communication, 2007; Montañez et al., 2007), indicating the broad generality of ecosystem behavior at this scale of resolution.

SUMMARY AND CONCLUSIONS

The analysis of terrestrial ecological patterns in the stratigraphic record requires the identification of isotaphonomic assemblages through time first within, and subsequently between, sedimentary basins at various paleolatitudes (DiMichele and Gastaldo, 2008). In addition, it is essential that isotaphonomic assemblages be evaluated within a genetic framework of sedimentological context such that artifactual patterns can be eliminated (Gastaldo and Demko, 2009). Sequence stratigraphic concepts provide criteria to delimit the genetic framework in coastal-paralic basins, providing a basis upon which persistence patterns can be identified. When the stratigraphic interval can be constrained chronometrically, true ecological patterns can be discerned and placed within a meaningful framework.

The present study has recognized >55 genetic cycles in the Upper Silesian Basin that encompass the Late Mississippian Ostrava Formation and Early Pennsylvanian Karviná Formation. Each Mississippian cycle is bounded at its base by a macroinvertebrate assemblage stratigraphically overlying a prominent coal or coal zone (the boundary interpreted as a ravinement [transgressive erosional] surface; see Liu and Gastaldo, 1992; Yang, 2007). Similarly, the top of the cycle consists of the last coal or siliciclastic interval overlain directly by lithologies in which a macroinvertebrate assemblage is preserved. Megafloral elements identified within each cycle—based on extensive borehole data and reports and analyzed using various multivariate techniques—show patterns of vegetational persistence within the basin. Single crystal U-Pb zircon ages from tonsteins in the Ludmila and Karel coals allow for calculation of cycle duration approaching 100 kyr in this part of the stratigraphy. Using the Hess and Lippolt (1986) date reported for sanidines recovered from the Otokar coal tonstein (Poruba Member), cycle duration approaches 120 kyr. Hence, vegetational persistence in this paleoequatorial region was retained with durations <1.8 myr.

The results of this study are comparable to those of younger (Pennsylvanian) peat-and-clastic accumulating transitional sequences (cyclothems) in which vegetational persistence is the rule. Hence, a pattern of paleotropical ecosystem persistence during the Late Paleozoic Ice Age began in the Late Mississippian and continued into the Late Pennsylvanian (with background turnover, extirpation, and wholesale replacement as identified in the literature), until stepwise global deglaciation caused a major restructuring of paleotropical floras in transition to a permanent ice-free world (Gastaldo et al., 1996; Montañez et al., 2007).

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