MEGAFLORAL PERTURBATION ACROSS THE ENNA MARINE ZONE IN THE UPPER SILESIAN BASIN ATTESTS TO LATE MISSISSIPPIAN (SERPUKHOVIAN) DEGLACIATION AND CLIMATE CHANGE

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ABSTRACT

A significant vegetational change occurs in the Late Mississippian (Serpukhovian, Namurian A) across the Enna Marine Zone (EMZ), Upper Silesian Basin, Czech Republic. All plant clades were impacted, including both spore-producing and seed-producing taxa; wetland taxa were unaffected. Similar vegetational responses are not identified elsewhere although, basinwide, thick marine zones (e.g., Barbora Marine Zone, BMZ) also developed at various times during the Serpukhovian. Examination of sedimentological and petrophysical (gamma-ray log) trends in both marine zones indicates that different mechanisms generated accommodation space during each interval. Placed in a genetic stratigraphic context, the EMZ records sedimentation in at least four (or more) genetic sequences, each equal in duration to individual 100-kyr cyclothems identified in the coalfield. Discrete maximum flooding surfaces (MFSs) with associated condensed sections and macrofaunas are prominent in distal areas and were identified using gamma-ray log responses. In contrast, the petrophysical expression of distal regions of the BMZ shows no strong positive gamma-log excursions interpreted as MFSs. Rather, this interval is a succession equal in duration to two cyclothems. The BMZ represents sedimentation in a glacial-interglacial cyclothemic framework; in contrast, the EMZ represents accumulation under continued eustatic sea-level rise in response to southern hemisphere deglaciation and global warming. Late Mississippian vegetational response to paleoequatorial climate change is interpreted to represent a shift toward greater seasonality, with an increased number of dry months (monsoonal rainfall pattern?) resulting in statistically significant extinction or extirpation several million years prior to the onset of maximum glaciation and sea-level drawdown at the Mississippian–Pennsylvanian boundary.

INTRODUCTION

Interpretations of climatic patterns prior to the onset of maximum Gondwanan glaciation in the early Carboniferous generally have been applied broadly across a hemisphere or region based on sedimentological and paleontological proxies. The Late Paleozoic Ice Age (LPIA) had been seen as a single, protracted glaciation, beginning in the Middle Mississippian (Visean) and extending into the mid-Permian (Cisuralian; e.g., Frakes et al., 1992; Crowley and Baum, 1992). Recent studies in South America, Antarctica, and Australia have called that interpretation into question and suggest the presence of multiple, smaller ice centers that occupied the supercontinent rather than a permanent ice sheet across the entirety of Gondwana (Lopez-Gamundí, 1997; Isbell et al., 2003; Fielding et al., 2006, 2008a). Although these centers were limited both spatially and temporally (e.g., Eyles and Eyles, 2000; Jones and Fielding, 2004; Eyles et al., 2006; Fielding et al., 2008b), oscillations between glacial

and interglacial phases have been recognized in far field records of the paleoequatorial zone. Such records are manifested by cyclothemic deposits (e.g., Veevers and Powell, 1987; Heckel et al., 1998; and many others) in which there is a well-preserved terrestrial plant-fossil record.

Shifts in megafloral and microfloral assemblages throughout the Permo-Carboniferous traditionally have been used to subdivide the late Paleozoic continental record biostratigraphically. The expression of these shifts in the paleotropics has been linked to regional or global changes in climate patterns that controlled the growth, reproduction, and sustainability of ecosystems and biomes (Gastaldo et al., 1996; DiMichele et al., 2001a, 2005). Such patterns have been well documented for the late Carboniferous in both mineral substrate (e.g., Pfefferkorn and Thomson, 1982; Pfefferkorn et al., 2008) and peat mire (e.g., DiMichele et al., 1996; Peppers, 1996) environments. The relative dearth of Mississippian data (Raymond, 1985, 1996), when compared to that for the Pennsylvanian, has precluded the recognition of similar, high-resolution sequences and vegetational responses during the buildup of Gondwana glaciation. With the analysis of a large, comprehensive data set derived from the cyclothemic sequence in the Upper Silesian coal basin, such patterns have now been recognized (Gastaldo et al., 2009) and the factors most likely responsible for vegetational turnover following long periods of persistence can be interpreted. This basin, spanning the Czech Republic and Poland, contains one of the most complete records of Visean–Serpukhovian–Bashkirian cyclothems in the Euramerican paleotropics. The present contribution will evaluate the paleontological and sedimentological record of two thick marine intervals in the Ostrava Formation, Czech Republic, over which vegetational changes have been identified and previously used to subdivide the stratigraphy. A model is proposed to account for the differences in vegetational response across these thick marine sequences that may be applicable to other parts of the Carboniferous record.

OSTRAVA-KARVINÁ COALFIELD

The late Paleozoic Upper Silesian Basin extends over an area of ~6500 km² (Fig. 1) and formed as part of the European Variscan fold belt. Approximately a third of the basin (1800 km²) is found in the Ostrava-Karviná coalfield of the Czech Republic, with correlatives known beneath the Carpathian Flysch nappes in south Moravia also (Fig. 1B; Dvořák et al., 1997). The area experienced a complex tectonic history (Kumpera and Martinec, 1995; Kumpera, 1997), and 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). Lithologies in the basin span the uppermost Visean to Serpukhovian (Namurian A) and attain thicknesses of >1500 m in the northwest, with more than 3200 m of siliciclastic sedimentary rocks and coals in the depocenter (Kumpera and Martinec, 1995). The total thickness of the Serpukhovian–Moscovian (Namurian A–Westphalian D) sequence in the Polish part of the basin exceeds 4600 m (Zdanowski and Żakowa, 1995).

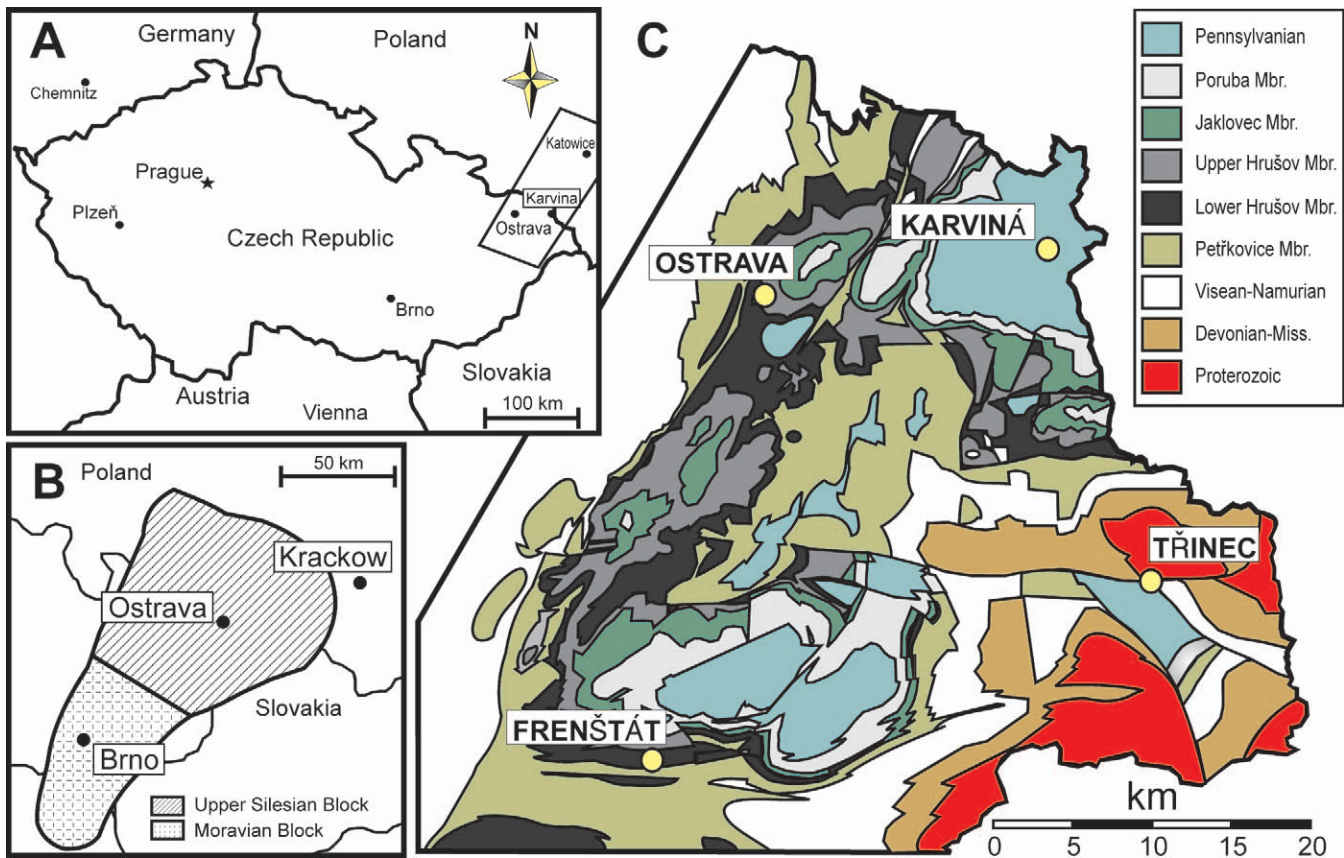Accumulation of the uppermost Visean–Serpukhovian paralic sequence

FIGURE 1—Geographic and geologic features of the Upper Silesian Basin. A) Locality map of central Europe with the Upper Silesian Basin outlined. B) General structural map showing the relationship between the Upper Silesian Block, which includes the Ostrava-Karviná coalfield, and the Moravian Block. C) Geographic distribution of only the Paleozoic rocks, including the members of the Ostrava Formation, in the Silesian Basin (after Dopita et al., 1997). Mesozoic and Cenozoic overburden, which may attain 2000 m in thickness in the southeast, has been removed from the illustration.

(Namurian A, Ostrava Formation) occurred within a foreland basin (Kumpera and Martinec, 1995) in which cyclothemic sequences of fossiliferous marine deposits are overlain by fossiliferous and coal-bearing continental deposits. Fully continental coal-bearing deposits of Bashkirian age (Namurian B–Westphalian A) attain thicknesses >1000 m (Karviná Formation; Kumpera and Martinec, 1995). Pennsylvanian coal-bearing intervals overlie fining-upward sequences of coarse-clastic fluvial regimes which, in turn, are truncated by fluvial incision (Pešek, 1994).

Ostrava Formation

The Upper Mississippian (Serpukhovian) Ostrava Formation consists of cyclical fossiliferous marine deposits overlain by coal-bearing continental successions (Havlena, 1986; Dopita and Kumpera, 1993). It is subdivided into four members; in ascending stratigraphic order, these are the Petřkovice, Hrušov, Jaklovec, and Poruba Members, each of which are several hundred meters thick (Figs. 1C, 2). These units traditionally have been separated based on the presence of volcanic tuffs (i.e., whetstones, Petřkovice-Hrušov contact; Dopita et al, 1997) or thick marine intervals. More than 200 macroinvertebrate taxa (Řehoř, 1977) are preserved in ~180 invertebrate-bearing beds aggregated into 27 groups (in ascending stratigraphic order, I–XXVII of Řehoř and Řehořová, 1972), of which the Enna (XVI), Barbora (XXI), and Gaebler (XXVII) Marine Zones are considered the most important stratigraphically (Havlena, 1982). These major marine intervals also occur in the Polish part of the basin and have been used to separate megacyclothems (Kotas and Malczyk, 1972). Combinations of invertebrate-bearing beds are interpreted to represent fully marine, *Lingula*-bearing brackish (estuarine), and freshwater (bivalve-dominated) assemblages (Řehoř and Řehořová, 1972; Řehoř, 1977). The Petřkovice and Hrušov Members have been assigned to

the lower Namurian E_1 goniatite subzone, whereas the Jaklovec and Poruba Members are considered to be equivalent to the E_2 subzone (Dopita et al., 1997).

Species of the lyginopterid pteridosperm genus, *Lyginopteris*, were used first by Patteisky (1937, 1957) as index taxa to delineate the terrestrial zonation of both Visean and Namurian strata. This practice continued (Kotasowa, 1975; Havlena, 1977; Purkyňová, 1977), with Purkyňová

FIGURE 2—Stratigraphic relationships in the Upper Mississippian Ostrava Formation, which is subdivided into four members: Petřkovice, Hrušov, Jaklovec, and Poruba. Each member is separated by a basin-wide, thick marine interval identified by roman numerals (as established by Řehoř and Řehořová, 1972). Arrows indicate the two marine intervals across which changes in macrofloral are compared.
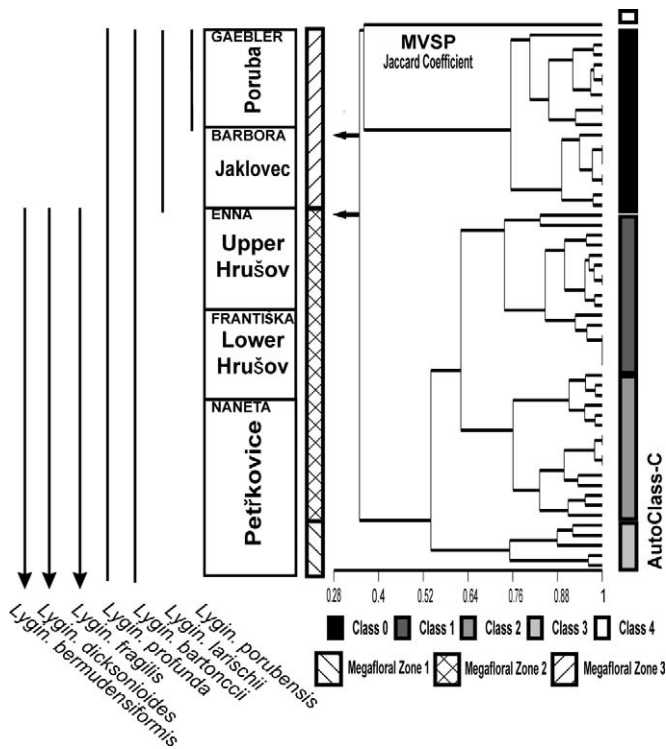
FIGURE 3—Biostratigraphic ranges of *Lyginopteris* species (left; first used by Patteisky, 1937, 1957), megafloral zones (center; Purkyňová, 1977, 1996b), and cluster analysis of megafloral taxa (right; Gastaldo et al., 2009) in the Ostrava Formation. Four classes of plant-fossil assemblages are identified in the Ostrava Formation (modified from Gastaldo et al., 2009). Arrows indicate the changes in megafloral assemblages considered in this paper.

(1977, 1996a, 1996b) recognizing three major floral associations in the Late Mississippian based on 46 taxa (Fig. 3). Her lowermost floral zone includes uppermost Visean and lowermost Serpukhovian strata, while the middle zone consists of assemblages preserved in the remainder of the Petřkovice and Hrušov Members, ending at the Enna Marine Zone. Purkyňová's (1977, 1996b) upper zone encompasses both the Jaklovec and Poruba Members, although Patteisky (1937, 1957) separated the Poruba Member based on the first appearance datum (FAD) of an endemic, *Lyginopteris porubensis*. Not surprisingly, a significant megafloral change (Florensprung; Gothan, 1913) occurs in the Karviná Formation above the mid-Carboniferous boundary, a feature that has been recognized throughout the paleotropics (e.g., Pfefferkorn and Gillespie, 1982; Raymond, 1996).

Gastaldo et al. (2009) identified patterns of vegetational persistence in a reassessment of Late Mississippian data in the Czech part of the Upper Silesian Basin using exploratory cluster analysis (Jaccard coefficients of presence/absence data in MVSP; Kovach, 2006) and autoclassification techniques based on Bayesian statistical analysis (Fig. 3). They found that macrofloral assemblages group into four distinct stratigraphic clusters, with assemblages persisting for an average of <18 cycles before changes in assemblage composition occurred. Geochronometric ages of single zircons, recovered from tonsteins in the Petřkovice Member, constrain cycle duration in the lower part of the formation. Dates were acquired using a GV isoprobe-T multicollector thermal ionization mass spectrometer equipped with an ion-counting Daly detector, and 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. Cycle duration based on chronometric ages of Petřkovice (Ludmila tonstein 328 ± 0.16 Ma) and Hrušov (Karel tonstein 328.01 ± 0.08 Ma) Member tonsteins ranges from 54 to 107 kyr, which overlaps the short period (100 ka) eccentricity cycle at the 95% confidence interval (CI).

Hence, Late Mississippian wetland ecosystems persisted for at least two million years before regional perturbation, extirpation, or extinction of taxa occurred (Fig. 3).

The marine zones recognized by Řehoř and Řehořová (1972) and Řehoř (1977) continue to be used as marker horizons in the Upper Silesian Basin because each is regionally extensive, may exceed 100 m in thickness, and distinctive changes in megafaunal diversity occur within each marine zone when compared with subjacent assemblages. In contrast, only a few significant changes in the composition of macrofloral clusters occur across marine intervals (Fig. 3). This raises questions as to the mechanism(s) responsible for the different vegetational responses across each of the thickest marine zones. The Enna and Barbora Marine Zones and the megafloral changes associated with them will serve as the case studies herein to evaluate these trends.

MATERIALS AND METHODS

Megafloral data, consisting of 18,910 identified fossil plants compiled from more than 265 drill-core reports housed in the Silesian Museum, Opava, were assigned to their respective cyclothems. These include taxa characterized as Flözferne (extra-basinal, pteridosperm- and fern-dominated assemblages preserved between coals and in marine sections) and Flöznahe (lycopsid- and sphenopsid-dominated assemblages associated with peat-mire accumulations) by Havlena (1961, 1971; see Gastaldo, 1996 for a discussion of these taphofloral concepts). Criteria for cyclothem recognition, identification of genetic sequences, and cyclothem names are presented in Gastaldo et al. (2009) and follow protocols proposed by Gastaldo et al. (1993), Liu and Gastaldo (1992), and Pashin (2004). Fifty-four genetic cycles were circumscribed in the Ostrava Formation.

Few outcrops of the Ostrava Formation exist, and those that are accessible are limited, weathered heavily, and overgrown. Stratigraphies and regional relationships were derived from borehole reports that were supplemented with examination of limited drill core at DPB Paskov, Paskov, Czech Republic, and the Polish Geological Survey core warehouse in Włodawa, Poland. Overthickened sections, such as those associated with the Orlová structure (Dopita et al., 1997) were omitted from consideration. In addition, a very limited set of borehole petrophysical data was acquired for review from the Czech Geological Survey–Geofond (www.geofond.cz), Prague, and the Polish Geological Survey, Sosnowiec. Petrophysical data include gamma and resistivity logs; gamma traces were recorded in total counts at the time of collection in the mid- to late 20th century without further processing and are presented, as such, in this study.

RESULTS

Enna Marine Zone

The regionally extensive Enna Marine Zone reaches a maximum thickness of ~210 m near the western and northwestern boundary of the basin and thins eastward to a minimum of 32 m (Figs. 4, 5A). The top of the zone marks the boundary between the Hrušov and Jaklovec Members and can be found in the subsurface of all mining districts (Fig. 4). The marine rocks thin toward what has been interpreted as the paleoshoreline and adjacent to structural highs, although contracted sections also are indicative of erosion in areas where lowstand incision has affected the unit. No formal or published detailed sedimentological description exists, because this marker horizon was identified paleontologically.

At least three marine zones are identified in the succession (Fig. 6A, Řehoř, 1977), and these are interpreted as indicative of pleiomesohaline (8‰–18‰; Winston, 1977) to polyhaline (18‰–30‰) and euryhaline (30‰–40 ‰) waters based on their systematic composition and spatial relationships. Rugose corals are among the taxa reported from the interval that have been used to interpret fully marine conditions (Weyer, 1977). Havlena (1982) placed these marine bands in a paleogeographic gradient
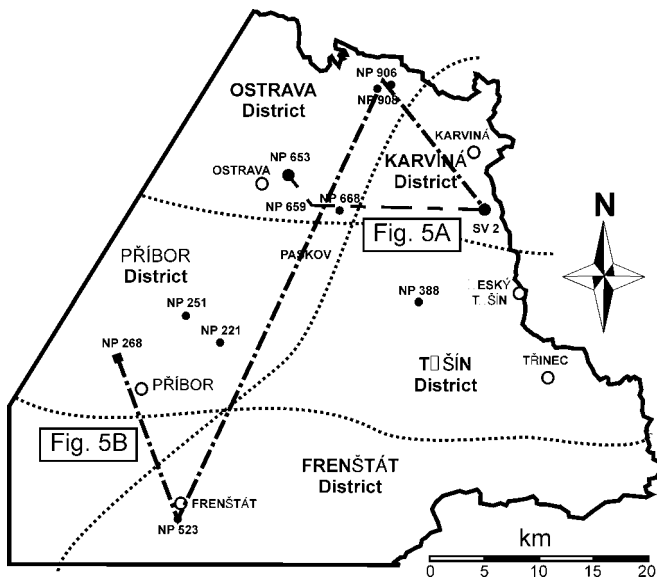
FIGURE 4—Outline map of the Ostrava-Karviná coalfield showing the mining districts active during the latter half of the twentieth century. Filled circles = boreholes used in this study. Subsurface cross sections illustrated in Figures 5 are shown: dashed line marks a west-east cross section of the Enna Marine Zone (Fig. 5A) and dashed-and-dotted line marks a west-east cross section of the Barbora Marine Zone (Fig. 5B).
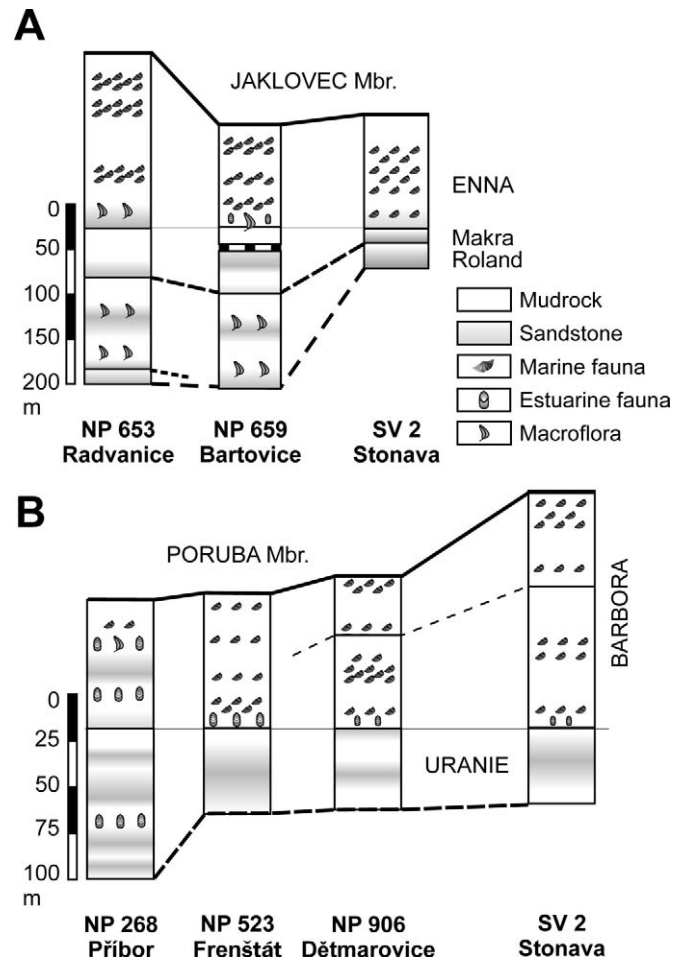

FIGURE 5—Generalized west-east, subsurface cross sections of the two major, thick marine intervals marking the boundaries between the Hrušov-Jaklovec, and Jaklovec-Poruba Members (modified from Dopita et al., 1997). See Figure 4 for location of cross sections. A) Section of the Enna Marine Zone across the Ostrava and Karviná mining districts. B) Section of the Barbora Marine Zone across the Přibor, Frenštát, Ostrava, and Karviná mining districts.

wherein western, southern, and central deposits (Fig. 4) were considered more continental and nearshore in character (based on the presence of weakly developed cyclothems), whereas correlative strata in the eastern part of the basin lacked evidence for cycles. He envisioned that the entire interval was deposited in a coastal-plain setting repeatedly transgressed by marine incursions that originated from the north.

Stratigraphic logs prepared during exploration provide a generalized lithologic summary of the marine zone (Figs. 5, 6A) across the coal basin. Boreholes from the Frenštát district (e.g., NP 523) show a basal erosional contact with several meters of erosionally bounded thin sandstones above. These are overlain by up to 100 m of silty sandstone and claystone in which up to six megafaunal horizons were found. Two of these fossiliferous beds are each one decimeter thick (1044 m and 1086.7 m; NP 537) and contain concentrated shell material, indicating time-averaged assemblages. When borehole stratigraphy is correlated with the gamma-ray log, each assemblage is preserved at an horizon where there is a strong increase in gamma-ray count. Hence, both assemblages are indicative of intervals of low sedimentation rates during which time a greater quantity of organic matter or clay clasts accumulated. The Enna Marine Zone is not as thick in other boreholes in the area (e.g., SV6; Fig. 7) and, in these cases, it is overlain by another marine zone (Šusta cycle, without intercalated, terrestrial, coal-bearing lithologies) of the Jaklovec Member. When the stratigraphic positions of the other preserved Enna megafaunas are correlated with the gamma-ray logs, these also are found at positive gamma excursions (Fig. 7).

Borehole logs of holes in the northern Těšín district (e.g., JA2; Fig. 7) are also characterized by a very short stratigraphic Enna Marine Zone dominated by siltstone or claystone. Two thin macrofaunal intervals occur, and when the stratigraphic position of these are correlated to the gamma-ray logs, they also are preserved where a strong excursion exists in the trace. There is no erosional contact at the upper boundary of the Enna Marine Zone. Rather, it is overlain directly by ~30 m of fine-grained lithologies (sandy siltstone that grades upward into a siltstone or claystone) in which five invertebrate horizons occur. The megafaunal elements of this marine interval are assigned to the overlying Jaklovec Member (Šusta cycle). Hence, as in the area of borehole SV6, there is a significant missing section (Figs. 5A, 7).

Boreholes farthest to the north in the Ostrava and Karviná districts show the greatest thickness of the Enna Marine Zone (Figs. 4, 5). Borehole NP 668 will serve as a representative example (Figs. 6A, 7). Sandy siltstone or claystone occur directly above an erosional boundary with the underlying Flora cycle identified, in this borehole, by the presence of a *Lingula* horizon (Dopita et al., 1997). The group is an ~150-m-thick interval of silty sandstone and sandy siltstone, with minor interbedded sandstone bodies that become more common up section. Macrofaunal assemblages are preserved exclusively in the fine-grained intervals in many individual zones; three major intervals over which successive, closely spaced fossils were recovered were identified as the lower (spodní), middle (střední), and upper (svrchní) Enna horizons. In addition, several unfossiliferous mudrock intervals are heavily bioturbated (Fig. 6A). Many invertebrate assemblages correlate with positive gamma-ray log excursions (Fig. 7).

Macrofloral Biostratigraphy.—The number of plant fossils identified from borehole reports varies across the mining districts. The greatest number and taxonomic richness are found in cores taken in the Frenštát district (Fig. 4) where representatives of each major clade occur, although the stratigraphic thickness of the interval generally does not exceed 120 m. Plant fossils are primarily frond fragments of ferns, pteridosperms, and plants of uncertain affinity (fern or pteridosperm); fragments of lianas
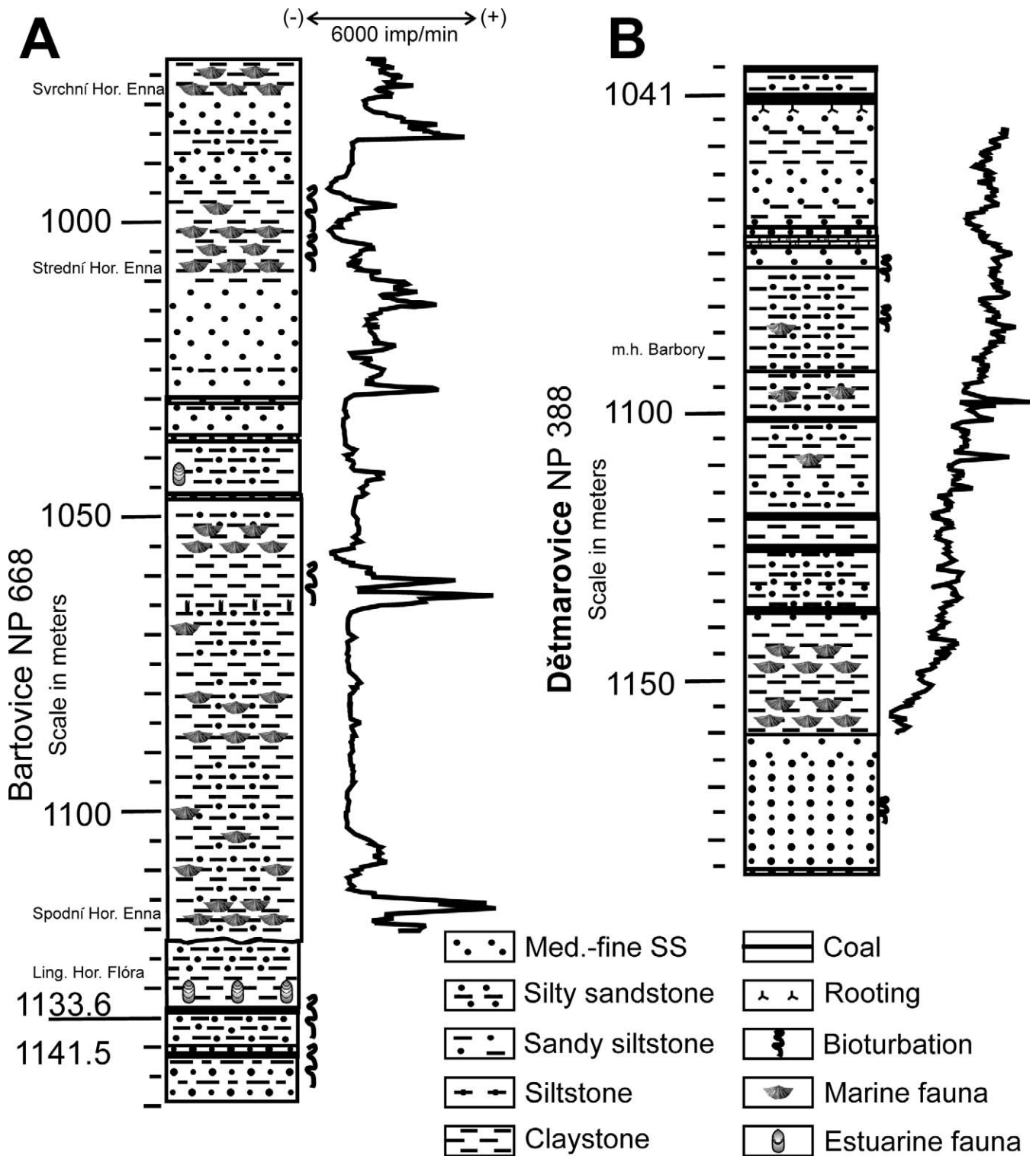
FIGURE 6—Stratigraphic, sedimentologic, and paleontologic logs of representative boreholes in the Enna and Barbora Marine Zones; scale in 5-m increments. See Figure 4 for borehole locations. A) Bartovice NP 668 borehole and gamma-ray logs, Enna Marine Zone (drilled 1961); lower (spodní), middle (strední), and upper (svrchní) Enna horizons are distinguished in the basin. B) Dětmarovice NP 388 borehole and gamma-ray logs, Barbora Marine Zone (drilled 1960–1961).

(vines; *Sphenophyllum*); and occasional axial remains of lycopsids (*Lepidodendron*) and sphenopsids (*Mesocalamites*). The number of occurrences and systematic diversity decreases northward through the coal field, where similar fern or pteridosperm leaf fragments predominate in the Těšín district. Here, the Enna attains a stratigraphic thickness of 128 m. This trend continues into the Karviná and Ostrava mining districts

where the thickest Enna sequences are reported (≤210 m). Plant fossils are found throughout the stratigraphic thickness of the marine zone and are not restricted to the interval directly above the underlying continental, coal-bearing cycle.

A dramatic change in assemblage composition occurs at the top of the Hrušov Member (Fig. 3), which also is reported in the Polish part of the
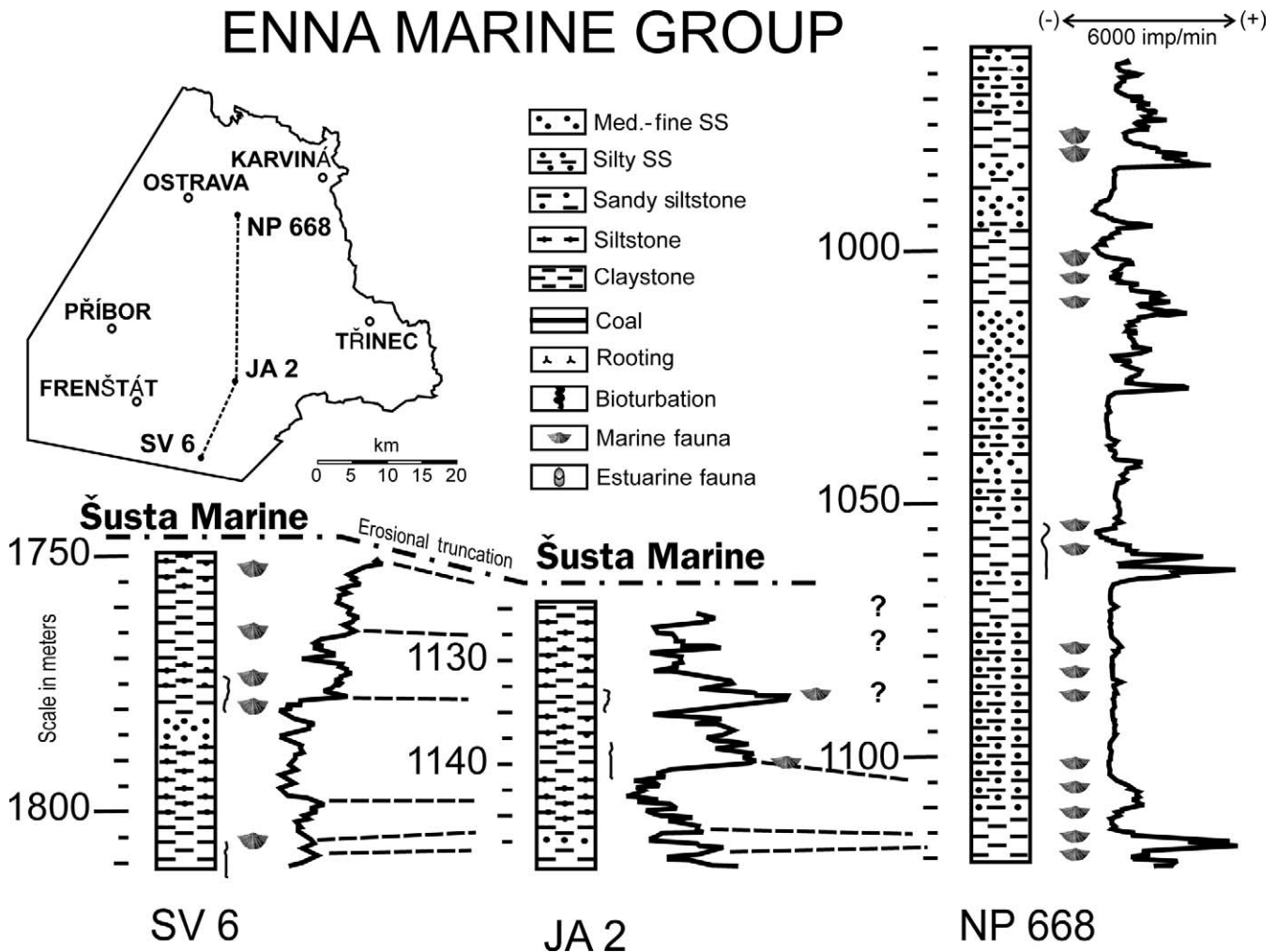
FIGURE 7—Proximal (SV 6)-to-distal (NP 668) transect of gamma-ray log profiles in the Enna Marine Zone on which the position of preserved megafaunas are shown. The Enna interval is reduced in the southern (proximal) part of the coal basin, where it is overlain directly by the Šusta Marine horizon of the Jaklovec Member. Maximum thickness of the Enna in the Czech Republic is toward the north, and the unit attains its greatest thickness in the Polish side of the basin. Imp/min = impulses per minute.

basin (Kotasowa, 1977). Purkyňová (1977, 1996b) noted that all macroflora that are characteristic of Culm-type assemblages (characteristically Visean taxa) have their last appearance datum (LAD) at the base of the Enna. These are considered to be elements of the Flözferne (allochthonous) facies and include understory taxa, such as *Sphenopteridium dissectum*, *S. bifidum*, and *Archaeopteridium tschermakii* (Table 1). Serpukhovian understory shrubs and trees that are extirpated are exclusively medullosan pteridosperms (*Neuropteris antecedens*, *Alethopteris willierei*). Many taxa of plants that had ground cover or liana growth habits also have their LAD in this interval, including lycopsids (*Eleutherophyllum mirabile*), ferns (*Alloiopteris goeppertii*), lyginopterid pteridosperms (*Lyginopteris bermudensiformis*, *L. fragilis*, *L. dicksonioides*), and taxa of uncertain fern or pteridosperm affinity (e.g., *Diplotmema patentissimum*).

Exclusively wetland taxa (e.g., lycopsids and sphenopsids) range through the marine zone, as well as plants adapted to non-hydric soils. Taxa that have their FAD in the overlying Šusta cycle (Jaklovec Member) are primarily those adapted to a groundcover or liana growth habit. These include lyginopterid (*L. larischii* and some *Mariopteris*) and medullosan (*Mariopteris bartovicensis*, *M. daviesoides*, *M. laciniata*) pteridosperms (Table 1). Understory taxa with FADs include medullosan pteridosperms (*Neuropteris loriformis*, *Neuralethopteris schlehanii*) and taxa of uncertain fern or pteridosperm affinity (*Sphenopteris sabiniensis*). One wetland, sphenopsid understory taxon (*Mesocalamites cistiiformis*) is recorded for the first time, and Purkyňová (1996b) noted that the sphenopsid

groundcover or liana taxon *Sphenophyllum cuneifolium* is encountered infrequently.

Barbora Marine Zone

The Barbora Marine Zone is a regionally extensive zone that marks the boundary between the Jaklovec and Poruba Members, and is restricted to the faulted areas of the Frenštát, Karviná, Příbor, and Těšín mining districts (Fig. 4, 5B). It has a maximum thickness of 130 m near the western boundary of the basin, and may be as thin as 20 m in central parts of the coalfield. Macrofaunal assemblages are very common in mudstone of the northwestern part of the basin, where there is no evidence of cyclical sedimentation (Havlena, 1982). Deposits to the east and south are described as exhibiting weakly developed cyclothems with thin coals, but Havlena (1982) noted that the easternmost sections are thinner and characterized by mudstone in which both fully marine (Weyer, 1977) and brackish-water taxa are preserved. He attributed a reduction of thickness in some borehole sections to depositional thinning, although erosion and loss through incision during sea-level drop cannot be discounted. In some sections, at least four marine and/or non-marine bands are identified (Fig. 5B). Řehoř (1977) stated that there is a systematic change in the Barbora horizon that represents a richer euryhaline association in which new endemic taxa first appear; a similar pattern is found in the megaflora (Purkyňová, 1996b). Řehoř and Řehořová (1972) provide some details on

TABLE 1—Last appearance (LAD) and first appearance data (FAD) for megafloral elements across the Enna Marine Zone, marking the change from the Hrušov to Jaklovec Members of the Ostrava Formation. Present data set supplemented by Purkyňová (1996a, 1996b).

Plant / Unit	Lycophytes	Sphenophytes	Pteridophytes	Pteridosperms	Pteridosperms or pteridophytes
Šusta Cycle: FAD		*Mesocalamites cistiiformis*		*Mariopteris bartovicensis*	*Sphenopteris sabiniensis*
				M. daviesoides *M. laciniata* *Neuropteris loriformis* *N. trnavkiana* *Neuralethopteris schlehanii* *Lyginopteris larischii*	
42 range-through taxa					
ENNA Marine Zone: FAD			*Pecopteris plumosa*		
ENNA Marine Zone: LAD	*Eleutherophyllum mirabile*	*Dichophyllites nemejcii*	*Alloiopteris goeppertii* *P. namurica*	*Alethopteris willierei* *Neuropteris antecedens* *L. bermudensiformis* *L. dicksonioides* *L. fragilis*	*Sphenopteridium dissectum* *S. bifidum* *S. silesiacum* *S. speciosum* *Archaeopteridium tschermakii* *Diplotmema patentissimum* *Sphenopteris sculptilefolia* *Cardiopteridium waldenburgense* *Rhodeopteridium moravicum*

changes at the family level and utilize tables of occurrence data to illustrate biostratigraphic ranges. Statistical analysis of macrofaunal changes has not been conducted to date; however, interpretations of assemblage tolerances in Řehoř and Řehořová (1972) and Řehoř (1977) are reiterated elsewhere in the literature (e.g., Dopita et al., 1997).

Borehole logs for the Barbora Marine Zone show a similar lithologic trend as described for other marine intervals. The sequence in the Frenštát district of the southern coalfield (Fig. 4) attains a thickness of <88 m, although many borehole logs depict the marine zone as being thinner. A typical stratigraphy in this part of the basin consists of thin sandstone bodies intercalated with mudrocks (e.g., NP 523; Fig. 8). Overall, sections coarsen upward to a thicker sandstone body which has an erosional upper contact. Preserved megafauna occurs in several discrete sandstone-siltstone or claystone horizons.

In the Těšín district, the maximum thickness of the zone is 53 m, although several boreholes in the area show a thinner interval. Highly fossiliferous mudrock overlies a thick basal sandstone (e.g., NP 388; Figs. 6B, 8), and there is a general coarsening upward sequence to the remainder of the section. Up section, the succession is characterized by thin (~0.5 m) sandstone bodies that are intercalated in sandy siltstone or claystone. Macroinvertebrate remains are preserved in the fine clastic intervals, where there is a noted increase in bioturbation toward the top of each interval. Fossil horizons correlate with positive gamma-log excursions (Figs. 6B, 8).

The marine zone in boreholes from the Karviná district may be up to 89 m in thickness. Similar to the Enna Marine Zone, three assemblage horizons have been identified (NP 905; Fig. 8). The lower (spodní) is preserved in siltstone that, depending upon the borehole site, may directly overlie the uppermost coal of the previous genetic cycle (Gastaldo et al., 2009). This assemblage is overlain by a coarsening-upward sequence that ends in a thick sandstone, which is overlain by the middle (střední) marine horizon in which both invertebrate and plant fossils are reported in siltstone. This middle interval coarsens upward to a sandstone that is overlain by fossiliferous sandy siltstone identified as the upper (svrchní) horizon. A coarsening upward sequence that ends in a thick sandstone caps the Barbora Marine Zone. Unlike the Enna, where bioturbation was noted in discrete intervals, the Barbora is characterized by bioturbation in both the fine and coarse clastic intervals. Although the invertebrate assemblages correlate with positive excursions in the gamma-ray log (Fig. 8), a macroinvertebrate assemblage is not preserved at every positive excursion.

Macrofloral Biostratigraphy.—Plant megafossils are preserved across all mining districts throughout the stratigraphic thickness of the Barbora Marine Zone. Similar to the trends recognized in the Enna, the greatest number of specimens along with the highest systematic diversity is found in the Frenštát district (Fig. 4), where representatives of each major clade occur. In addition to the typical megafloral elements, an anomalous taxon, *Dicranophyllum brevifolium*, is reported as a singleton occurrence in several cycles (Fig. 9). The specimen is a terminal axis around which are arranged small lanceolate leaves. *Dicranophyllum* is reported in the Westphalian C of Central Bohemia (Pešek et al., 2001) and is more characteristic of late Permian and early Mesozoic megafloras reported from the early Permian of Texas (e.g., DiMichele et al., 2001b). Although the diversity of samples remains the same northward into the Karviná district, the number of occurrences decreases. There are limited data from the Těšín district, where the thickness of the marine zone has been reduced from erosion and emplacement of the overlying Jaklovec Member.

The dissimilarity between megafloras below and above the Barbora Marine Zone is more a function of FADs in the overlying Poruba Member than loss of taxa as in the Enna Marine Zone. This manifests itself in the results of the cluster analysis (Fig. 3) where the overlying assemblages are more similar to those of the underlying cycles. Purkyňová (1996b) noted that the flora becomes more Pennsylvanian in aspect with the addition of new taxa in the Poruba Member. Similar to the trend across the Enna Marine Zone, lycopsids and sphenopsids (wetland trees and understory) are unaffected. Systematic turnover occurs in the lyginopterid pteridosperms (*L. profunda* is replaced by *L. porubensis*; Table 2), which exhibit a groundcover or liana growth habit, understory medullosan pteridosperms, and taxa of uncertain fern-pteridosperm affinity. These include the LAD of *Neuropteris reticulopteroides*, which is replaced by three other neuropterid taxa, and the LAD of *Sphenocyclopteridium bertrandii*, which is replaced by two sphenopterid taxa.

DISCUSSION

Stratigraphic Implications of Ostrava Formation Marine Zones

Early workers (e.g., Havlena, 1982) interpreted the depositional environments of the marine zones as shallow water bays in the west-northwest that became more terrestrial in character to the south (lagoons and coastal plain lakes preserving invertebrates). More recently, such marine zones were placed in a platform setting developed within the foreland basin
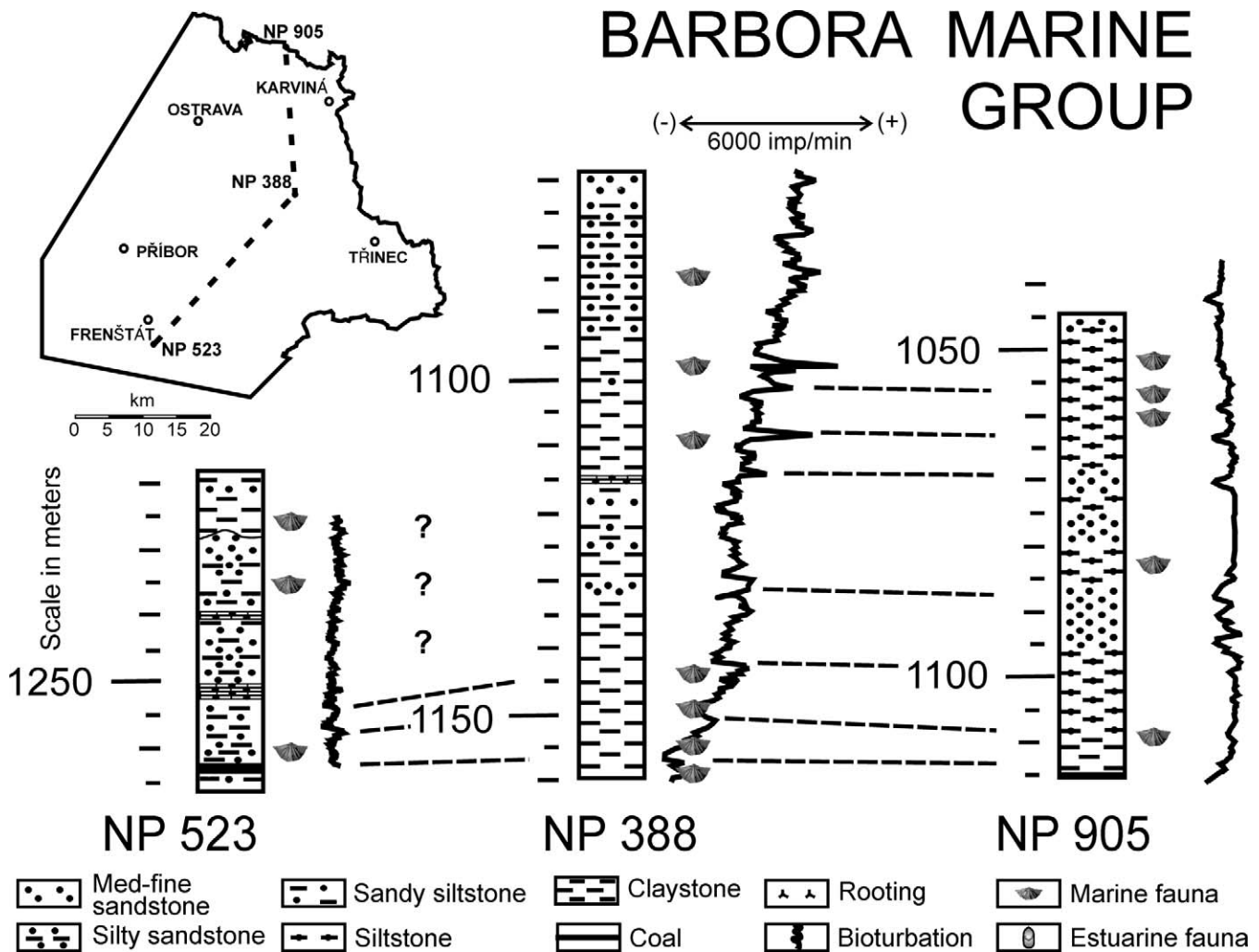
FIGURE 8—Proximal (NP 523)-to-distal (NP 905) transect of gamma-ray log profiles in the Barbora Marine Zone on which the position of preserved megafaunas are shown. The Barbora interval is reduced in the southern (proximal) part of the coal basin and its maximum thickness occurs toward the Polish border. The unit attains its greatest thickness in Poland.

(foredeep; Dopita et al., 1997), in which open-marine to freshwater assemblages are preserved. Freshwater assemblages composed of the bivalves *Carbonicola* and *Naiadites* (Řehoř and Řehořová, 1972; but see Eager, 1977 who interprets the *Carbonicola* in a shallow-water, marginal marine [brackish] setting) in this scheme are preserved close to shore,
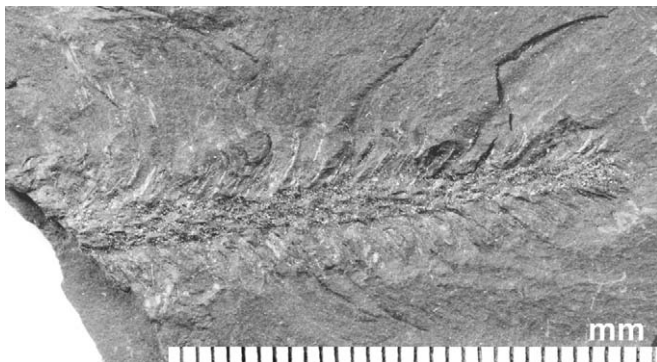

FIGURE 9—Photograph of cf. *Dicranophyllum brevifolium*, a terminal branch with narrow, elongate leaves identified in the lower Petřkovice (Leonard, Bohumila, Pavel cycles), Hrušov (Enna cycle), and Poruba (Barbora cycle) Members. The genus is reported from the late Paleozoic and early Mesozoic.

where freshwater was discharged from fluvial sources or in proximal, coastal-plain sites.

All publications on the Upper Silesian Basin, to date, interpret each marine interval as the upper part of a traditional cyclothem (Havlena, 1986; Dopita and Kumpera, 1993) that was originally considered to have developed under intermittent tectonic control. Although still considering these intervals as the upper part of a cyclothem, Skoček (1991) re-evaluated the coalfield paradigm and interpreted cyclothems as having been glacio-eustatically controlled. He considered these correlative to the transgressive phases of Ramsbottom's (1979) mesothems in Europe and Ross and Ross' (1985) fourth-order cycles in North America. More recently, Gastaldo et al. (2009) interpreted the fossiliferous marine intervals as the base of a transgressive-erosionally bound cycle, each of which is equivalent to a low fourth- or high fifth-order (100 ka) cycle. In this model, fully marine macroinvertebrates preserved directly above coals are equivalent to assemblages found in condensed sections at and overlying a Maximum Flooding Surface (MFS), as identified in North America (Liu and Gastaldo, 1992; Gastaldo et al., 1993; Pashin, 2004).

The use of petrophysical data in conjunction with sedimentological and paleontological evidence allows for thick, monotonous mudstone sequences to be resolved into depositional packages (genetic sequences *sensu* Galloway, 1989). Gamma-ray peaks in mudrock are related to various uranium and thorium concentrations, with brackish-water, *Lingula*-dominated beds showing the lowest gamma response and marine anoxic

TABLE 2—Last appearance (LAD) and first appearance data (FAD) for megafloral elements across the Barbora Marine Zone, marking the change from the Jaklovec to Poruba Members of the Ostrava Formation. Present data set supplemented by Purkyňová (1977, 1996a, 1996b).

Plant / Unit	Lycophytes	Sphenophytes	Pteridophytes	Pteridosperms	Pteriodsperms or pteridophytes
Filip-Gustav Cycle: FAD				*Lyginopteris porubensis*	*Sphenopteris praecursor*
				Neuropteris bohdanowiczii	*S. hollandica*
				N. kosmannii	*Rhodeopteridium tenue*
				N. multinervosa	
46 range-through taxa				*Alethopteris tectensis*	
Barbora: LAD		*Sphenophyllum sublaurae*		*Lyginopteris profunda*	*Sphenocyclopteridium bertrandii*
				N. reticulopteroides	

black shales the highest (O'Mara and Turner, 1997). In distal offshore marine sites, increased radioisotope concentrations occur where clay-sized clasts undergo extremely low sedimentation rates (Leeder et al., 1990), although various lithologic attributes, the abundance of land-plant detritus, and original bottom-water conditions can affect radiogenic concentrations (Wignall and Maynard, 1993; O'Mara and Turner, 1997). Where possible, correlation between sites using gamma response must be used in a biostratigraphic framework to insure accuracy and equivalency.

According to Galloway (1989), bounding hiatal surfaces separate stratigraphic intervals that reflect significant interruptions in basin depositional history. Although several unconformities are acknowledged, MFSs are the bounding hiatal surfaces for both the lower and upper boundaries of a genetic stratigraphic sequence (GSS). Offlap (regressive) and onlap (transgressive) components can be identified within the GSS (Gastaldo et al., 1993). More recent models place the MFS nearly coincident with the highest stand of eustatic sea level, rather than the time of maximum rate of rise (Posamentier and Allen, 1999). The stratigraphic interval directly above the MFS commonly is characterized by sediment starvation and radiogenic enrichment, which appears as a positive excursion in gamma-ray logs (e.g., Pashin, 2004). Low sediment-accumulation rates also allow for more reworking by burrowing organisms of the deposits in the condensed section (Gibson, 1990; Liu and Gastaldo, 1992). Hence, in the absence of preserved macroinvertebrate assemblages, burrowed intervals correlative with excursions in gamma-ray logs can also be used to interpret the presence of an MFS.

Both the Enna and Barbora Marine Zones record thick deposits in a proximal to distal, open-marine trend in the basin. A higher proportion of coarser-grained sandstone units occur toward the south (Frenštát district), with decreasing sandstones northward (Karviná district and into Poland; Fig. 4); these differences can be seen in the gamma-ray logs (Figs. 7, 8). Based on gamma response, it is possible to separate the distalmost, thickest intervals into parasequences (separated by flooding surfaces) and genetic sequences (separated by MSFs; Galloway, 1989). When the genetic sequences are compared, there is an obvious difference between the character of the two marine zones (Fig. 10).

The gamma-ray signature in the distal deposits of the Enna Marine Zone (Fig. 10A) allows for the recognition of at least four, possibly six, genetic sequences (≈cyclothems) in this part of the basin, although a very limited number of petrophysical logs make correlation and analysis at the mining-district level impossible. These rocks exhibit two principal sedimentological patterns. Following the basal excursion in gamma response (MFS at 1116.5 m), the parasequences in the lowest ~45 m indicate the presence of a thick mudrock interval that is interpreted as an open-shelf environment. Following the MFS at 1064 m, the gamma response is more indicative of an inner-shelf environment where sandstone bodies are intercalated in fine-grained sediment. The third genetic sequence (1028–990.5 m) is characterized by an increase in sandstone bodies, whereas the fourth sequence (990.5 m) is indicative of a coarsening upward parasequence capped by coastal plain, coal-bearing lithologies. Hence, the Enna Marine Zone represents at least four, probably more (because this core does not express the maximum thickness of the interval), cryptic cyclothems.

The gamma-log response in the Barbora Marine Zone (Fig. 10B),

which is in a more distal paleogeographic position (Fig. 4), shows a suppressed petrophysical signature. There are no strong positive excursions as in the Enna Marine Zone; rather, the response is similar to the basal interval of parasequences in the former. At least one, and possibly two, relative changes in sea level can be interpreted in the stratigraphy, although all parasequences may belong to a single genetic sequence. Hence, the sequence stratigraphic signals differ in each marine zone and the amount of time represented by the Barbora Marine Zone ranges from 33% to 50% or more of that represented in the Enna Marine Zone.

Role of Eustacy in Ostrava Marine Zones

The controls of both tectonics and eustacy on Carboniferous cyclothem stratigraphy have been debated (e.g., Heckel, 1986; Klein and Willard, 1989; Klein, 1990; Heckel et al., 1998), with a general agreement that the role of each is spatially and temporally dependent upon the basin under consideration. In individual cyclothems it is possible to identify stratigraphic intervals wherein the accommodation space was generated either tectonically (Gastaldo et al., 2004) or eustatically (e.g., Demko and Gastaldo, 1992, 1996), allowing for these controls to be differentiated in a basinal context over time (e.g., Pashin, 2004).

During warm intervals in Earth history, such as the Cretaceous, long stratigraphic intervals of exclusively offshore deposits may indicate times when the subsidence rate was in near equilibrium with the accumulation rate, resulting in reduced coastal progradation and a sustained series of marine deposits (Posamentier and Allen, 1999). Under these conditions, accommodation space is filled about as rapidly as it is created, and water depth remains relatively constant from one genetic sequence to the next; in essence, there is no net shift of facies. Such patterns characterize parts of the Enna and Barbora Marine Zones.

During cold intervals in Earth history, when extensive continental polar glaciers expanded and contracted, prolonged accumulation of genetic sequences composed exclusively of marine deposits (e.g., Fig. 10A, 1100–1070 m; Fig. 10B) in far field, equatorial basins is more indicative of deglaciation pulses, during which subsidence rates did not change effectively, but sea level continued to rise in response to rapid melting. Deglaciation during the Pleistocene records such a phenomenon, with research indicating that pulsed eustatic rise has been accompanied by rapid deepening on a global scale (e.g., Blanchon et al., 2002; Clark et al., 2002; Webster et al., 2004). Accommodation filled during such a rise in sea level, when sufficient sediment load has been transported seaward, will result in genesis of a parasequence.

Rapid, basin-wide transgression, resulting in offshore marine invertebrate assemblages that are preserved above coals or estuarine deposits, are thus indicative of eustacy (e.g., Liu and Gastaldo, 1992; Pashin, 2004). This is the common stratigraphic relationship in the Upper Mississippian of the Upper Silesian Basin, and it appears from gamma-ray log responses that both the Enna and Barbora marine intervals exhibit a pulsed record of accommodation generation and sediment fill, mimicking trends in the recent.

Forcing Mechanisms Responsible for Vegetational Change

Late Mississippian Euramerican coastal plains of equatorial proto-Pangaea were colonized intermittently by vegetation adapted either to
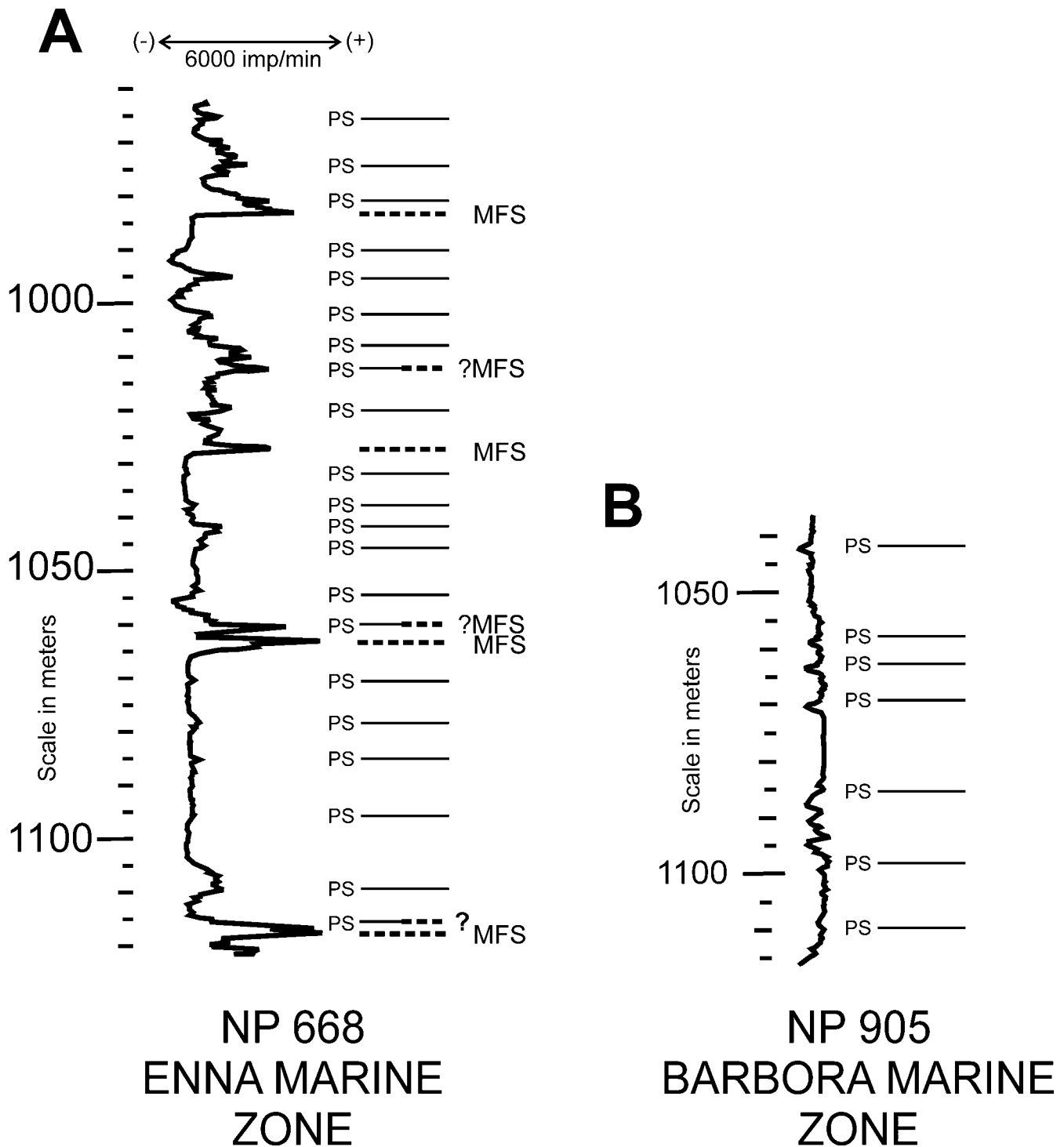
FIGURE 10—Comparison between gamma-ray signatures in distal boreholes of the Enna and Barbora Marine Zones (see Figs. 7, 8 for borehole localities), along with a genetic stratigraphic interpretation of the gamma-ray traces. A) Bartovice NP 668 log in which strong positive excursions are interpreted as maximum flooding surfaces (MFS). Parasequences (PS) occur between MFSs. The basal parasequences are interpreted to show a stable outer shelf (below wave base) environment, whereas upper parasequences show coarsening-upward signatures. B) Dětmarovice NP 905 log in which there is an absence of strong positive excursions similar to those of Fig. 10A. The gamma-ray log is equivalent to the lowermost 40 m of the Enna gamma-ray log.

wetlands (peat or mineral substrates) with high water tables or to better-drained soils in which water-table fluctuations caused physiological stress at times. These wetland and mineral-substrate biomes are also known from the late Carboniferous and persisted into the Permian (DiMichele et al., 2001a; Montañez et al., 2007). Climate, as well as the physical and chemical processes in operation that support and sustain biomes, control the distribution of vegetation across any landscape (DiMichele

and Gastaldo, 2008). Although climatic perturbations can be identified in coal beds and peats using petrographic analyses, such as intervals of seasonality or drying (White et al., 1995), such short-term variability is intrinsic to all such wetland and mineral-substrate ecosystems. Short-term climate variation does not produce major biotic change at the biome level, although ecosystems may experience background turnover in constituent clades following such disruption. Prominent changes in ecosystems at the
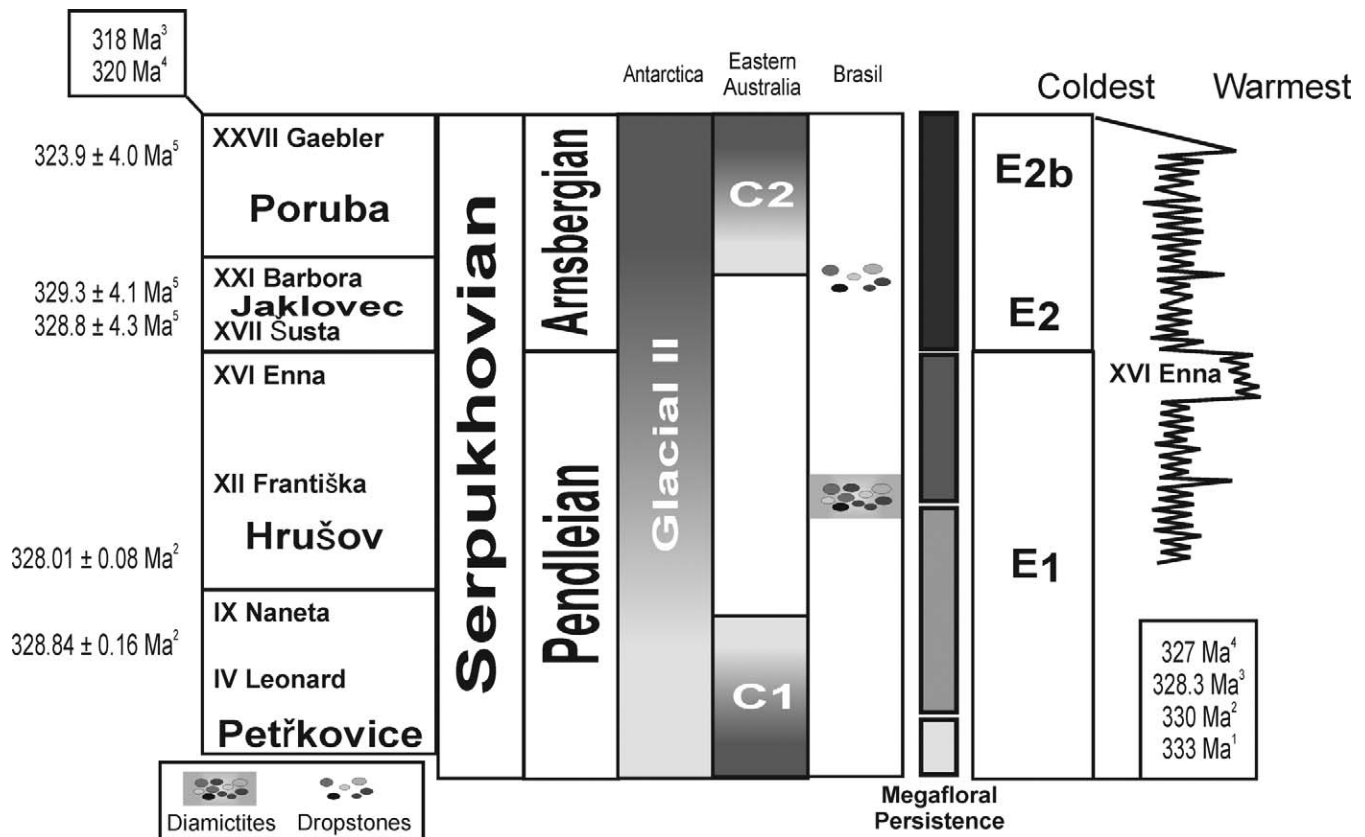
FIGURE 11—Late Mississippian megafloral assemblage persistence (Gastaldo et al., 2009), interpretation of climate oscillations, and the recognition of a late Serpukhovian warming interval resulting from deglaciation pulses as interpreted from gamma-ray logs of the Enna Marine Zone. Using cycle estimates of Gastaldo et al. (2009), the duration of deglaciation and paleotropical warming resulting in significant vegetational perturbation was at least 500 ka. Boundary dates from Harland et al. , 1990 (superscript 1), Gastaldo et al., 2009 (superscript 2), Gradstein et al., 2004 (superscript 3), and Menning et al., 2006 (superscript 4). Chronometric dates from tonsteins in the Petřkovice, Hrušov, Jaklovec, and Poruba Members, recalibrated from Lippolt and Hess, 1986 (superscript 5) are from Gastaldo et al., 2009 (superscript 2). Glacial records of Antarctica are from Isbell et al. (2003), of eastern Australia are from Fielding et al. (2008a and 2008b), and of Brazil are from Rocha-Campos et al. (2008).

regional or global scale are a temporal function of climate change on longer intervals of time (e.g., Milanković orbital forcing; Berger, 1980). Such is the response of Late Mississippian vegetation in the Upper Silesian Basin.

The significant change in both the megaflora (Fig. 3) and microflora (miospore zones; Dopita et al., 1997) occurs at the boundary between the Hrušov and Jaklovec Members across the Enna Marine Zone. A similar vegetational response is not present at the boundary between the Jaklovec and Poruba Members across the Barbora Marine Zone. Similarly, there is no significant change in the Hrušov Member, Františka Marine Zone, nor in the Petřkovice Member, Naneta Marine Zone (Gastaldo et al., 2009). Hence, some perturbation occurred at the time during which the Enna Marine Zone accumulated in the Ostrava-Karviná coalfield. The same vegetational responses at this boundary are documented throughout the basin in both the Czech Republic (Purkyňová, 1996b) and Poland (Kotasowa, 1987), and in other parts of Europe (Van der Zwan et al., 1985; change from CN to TK palynozone of Stephenson et al., 2008). Not surprisingly, taxa adapted to wetland soils (Flöznahe assemblage) are unaffected at either stratigraphic transition, as such conservative taxa persist in wetland refugia (DiMichele et al., 2001a, 2001b). Rather, where significant change occurs at the Enna, systematic loss and replacement is focused on plants in mineral substrate soils that grew as either ground cover-liana or understory (Flözferne assemblage; Gastaldo, 1996). The extinction (or extirpation) that occurs at the Enna horizon affected plants in several clades, including lycopsids (e.g., *Eleutherophyllum*), sphenopsids (*Dichophyllites*), ferns, and pteridosperms (compare Tables 1, 2).

Hence, the turnover and replacement was not restricted only to spore-producing or seed-producing taxa, but was systematically more widespread.

It is evident from the petrophysical data that the durations of these two marine zones differ and that different forcing mechanisms are responsible for their stratigraphic records. When the gamma-ray responses of the Enna and Barbora zones are compared (Fig. 10B), prominent positive excursions (condensed sections) characterize the former and are infrequent in the latter (Fig. 8). As noted above, the Enna Marine Zone represents at least four, and perhaps six, genetic sequences. Each sequence is considered equal in duration to others (cyclothems) in which both marine and continental lithologies are identified in the basin (Gastaldo et al., 2009), and each is considered to be controlled by fluctuations in glacio-eustacy (see Demko and Gastaldo, 1996, for criteria). In contrast, the Barbora Marine Zone consists of possibly two genetic sequences; these may be solely a function of eustacy, although tectonic subsidence cannot be ruled out for generation of accommodation. Although tectonics undoubtedly played a role in the development of accommodation space over the long duration of both stratigraphic intervals, the Enna Marine Zone records a far-field record of deglaciation pulses.

The early Carboniferous glacial record in the southern hemisphere varies from continent to continent, with evidence for spatially and temporally limited glaciation and deglaciation (Fig. 11). Isbell et al. (2003) recognize a single glacial interval of persistent ice (Glacial II) in Antarctica throughout the Serpukhovian, whereas Fielding et al. (2008a, 2008b) document two episodes of glaciation in eastern Australia. Recently,

Rocha-Campos et al. (2008) tentatively extended the base of the paly-nologically defined Pennsylvanian Itararé Formation of Brazil into the Serpukhovian, based on a SHRIMP zircon age of 323 Ma from near the base (Rocha-Campos, 2008, personal communication). If this age assignment is correct, diamictites occur near the middle of the stage, within the Pendleian (326.4–326 Ma), and dropstones are reported from the upper part, within the Arnsbergian (326–325 Ma).

González-Bonorino and Eyles (1995) suggested that maximum South American glaciation occurred in the early Serpukhovian (Visean–Namurian A, 325 Ma), although sedimentological evidence of this build-up is not extensive in Gondwana due to subsequent tectonism and sub-sidence patterns. There is evidence in this stage for hemispherical buildup of ice (Stanley and Powell, 2003) with the recognition of glacio-marine deposits in Siberia (Frakes et al., 1992), although southern hemisphere continents supported the maximum aerial extent of glaciation. Limarino et al. (2002) documented a Namurian–early Westphalian transgressive sequence in the Paganzo and Río basins in western Argentina including (1) Namurian–Westphalian marine brachiopods, bivalves, and crinoids (Limarino et al., 2002); (2) a latest early Carboniferous (=Serpukhovian) palynological assemblage (Césari and Limarino, 1992); and (3) marine microplankton (Gutierrez and Limarino, 2001). All are preserved over glacial diamictites. Field relationships show a paleogeography of open-marine (invertebrates and acritarchs) environments in the west and con-tinental or shallow-marine deposits (palynomorphs) in the east. The diam-ictites in the lower part of the Agua Colorado Formation preserve a Na-murian palynoflora (Limarino and Gutierrez, 1990), leading Limarino et al. (2002) to conclude that the transgression (deglaciation) cannot be older than early Namurian in age.

Physical evidence of southern hemisphere deglaciation in the Serpu-khovian (e.g., Limarino et al., 2002), prior to the maximum glaciation and drawdown responsible for the Mississippian–Pennsylvanian (mid-Carboniferous) unconformity, is coincident with stable isotope records (Bruckschen et al., 1999) and conforms to the sequence stratigraphic pat-tern exhibited in the Enna Marine Zone of the Upper Silesian Basin. Changes in glacial buildup and melting in the Serpukhovian also are supported by geochemical proxies that include a major shift in $\delta^{18}O$ values at the Visean–Serpukhovian transition, accompanied by a rise in $\delta^{13}C$ values of >3‰ (Bruckschen et al., 1999). These $\delta^{18}O$ data exhibit large-scale cyclicity, which is interpreted to reflect cooling-warming (glacial-interglacial) trends, although not at the scale of cycle resolution available in the Czech-Polish sedimentological record. What is of interest is the dramatic shift to more negative average $\delta^{18}O$ values in the mid-Serpukhovian (Bruckschen et al., 1999, fig. 6). Because they do not rec-ognize any physical evidence for such an event, Bruckschen et al. (1999) questioned the validity of this isotopic shift at ca. 323 Ma; however, such a shift of approximately −8‰ $\delta^{18}O$ values reflects widespread deglaci-ation in response to a major global warming event. Based on the estimate of average cycle duration in the Ostrava Formation (Gastaldo et al., 2009), and a mid-Carboniferous boundary age of 318 Ma (Gradstein et al., 2004) to 320 Ma (Menning et al., 2006), the derived timing of this shift is roughly coincident with deposition of the Enna Marine Zone.

The effects of late Mississippian deglaciation in the southern hemi-sphere have been recorded in the marine invertebrate record. In their analysis of extinction dynamics using Sepkoski's (1986) data, Raup and Boyajian (1988) first noted that long-ranging bivalves had a higher ex-tinction rate in the Serpukhovian than in adjacent stages. Raymond et al. (1990) showed an increase in brachiopod extinction in the mid-Namurian A, with a concomitant decrease in origination rates at this time. A similar extinction pattern in the early Serpukhovian was identified by Stanley and Powell (2003), who evaluated all marine invertebrates, and Powell (2008), who documented this trend in the Appalachian Basin. Thus, the Mississippian marine crisis began during the Serpukhovian stage. Be-cause the systematic losses cut across functional, physiological, and eco-logical lines, a physical rather than a biological mechanism is considered to have driven the extinction pattern (e.g., Raup and Boyajian, 1988;

Powell, 2008). That physical mechanism is proposed to be a change in global, rather than regional, climate that was influenced by tectonic uplift (Pfefferkorn et al., 2008). Such global climate change is recognized for the turnover and extinction patterns identified at the mid-Carboniferous (Serpukhovian–Bashkirian) boundary (e.g., Raymond et al., 1989, 1990, and others). Climate change in the Serpukhovian, however, has not been identified to date as a driving mechanism for biological turnover.

The plant-growth strategies affected by the mid-Serpukhovian warm interval identified herein (Fig. 11) were those restricted to groundcover, lianas, and understory shrubs and trees in the lycopsid, fern, and gym-nosperm (pteridosperm) clades. The extinction or extirpation of these plants was in response to a change in growth conditions (DiMichele and Gastaldo, 2008). The affected taxa are considered to have been centered ecologically in mineral substrate soils, although some are known from wetland conditions, indicating a wider range of soil-moisture tolerance for these taxa. The loss of a taxon from its biogeographic range is the result of its inability to sustain a population under newly established physical or chemical conditions. The dramatic systematic change in the late Serpukhovian at the Enna Marine Zone indicates the establishment of such conditions, which ultimately resulted in physiological stress and the demise of selected taxa.

There is some debate as to the type and magnitude of climate change in the Euramerican paleotropics during the LPIA (Fielding et al., 2008a, 2008b). Some authors envision oscillations in rainfall patterns and climate analogous to the Neogene (e.g., Tandon and Gibling, 1994), while others consider non-analog conditions to have prevailed in the wake of the as-sembly of the supercontinent (e.g., Cecil, 1990; Cecil et al., 2003). Under these two contrasting views of paleoclimate and paleoprecipitation dis-tribution, glacial maxima are interpreted either as (1) relatively dry (Tan-don and Gibling, 1994) with well-drained soils developed within the in-terfluves (Martino, 2004) colonized by fire-prone gymnosperm and fern communities (Falcon-Lang, 2004), or (2) relatively wet with the initiation of peat mires (Cecil, 1990) that are accompanied by intercalated silici-clastics and intervals of more seasonal drying. During interglacial times, the opposite climatic conditions would have prevailed. In the Serpukhov-ian of the Appalachian Basin, Cecil (1990) envisions the paleoclimate to have oscillated between semi-arid (aridosols, vertisols, and lacustrine car-bonates) to wet-dry tropical climates, resulting in planar mires during the wetter intervals when the Intertropical Convergence Zone was centered around the equator (Rowley et al., 1985; Lottes and Ziegler, 1994). Sub-sequent changes in climate signature in the rocks through the Pennsyl-vanian are considered a function of continental movement through the equatorial belt. Climate oscillation between wet and dry extremes gen-erally is regarded to be expressed in each cyclothem, although wide var-iance must have existed as a function of the phase relationships between obliquity, precession, and eccentricity cycles and their effects on glacial-interglacial times. The question arises as to what type of climatic change in the continental paleotropics of the late Serpukhovian resulted in the systematic turnover and loss recorded in the vegetation of the Upper Silesian Basin.

As Jackson (2006) notes, gradual or abrupt changes in ecosystems occur when the dominant taxa or functional types are replaced by others in response to environmental change or severe and irreversible (very short-term; 10^3 years) disturbance. The loss or replacement of a taxon is an individualistic response to the perturbation, and such responses can occur over a variety of time scales without necessarily affecting ecosys-tem structure. Such a pattern is witnessed throughout the majority of the Ostrava Formation where background turnover from cycle to cycle main-tains overall assemblage similarity for up to a few million years before significant systematic change occurs (Fig. 3; Gastaldo et al., 2009). One reason is that the dominant plants in the landscape (those with large populations that have the highest probability of contribution to a fossil-plant assemblage; DiMichele and Gastaldo, 2008) either tolerated the wider extremes in climate variation during 1-ka and 10-ka (or more) cycles or contracted their range into a part of the landscape near the

boundaries of their physiological thresholds during adverse climatic times. When co-occurring assemblages are defined by their dominant taxa (e.g., Flöznahe and Flözferne), then each assemblage has a characteristic niche defined by the environmental responses of the dominant species (Mosbrugger and Utescher, 1997; Jackson, 2006). With environmental change may come a change in species composition with concomitant changes in assemblage properties. It is not possible in the Serpukhovian to assess millennial-scale responses to tropical aridity, brought about by changes in atmospheric circulation patterns, as can be done for the Holocene (e.g., Mayewski et al., 2004). The best we can hope for is to evaluate ecosystem-biome response at the resolution of a cyclothem (100–400 ka) due, in large part, to the physico-chemical constraints of fossil-plant preservation and sampling (DiMichele and Gastaldo, 2008).

Because the plant-fossil record of cyclothems remains consistent over millions of years, it suggests that the short-term fluctuations in climate, identifiable at the millennial scale in the Holocene, in reality are background noise in the overall response of plants across the late Mississippian (and Pennsylvanian; Pfefferkorn et al., 2008) landscape. When there is a significant reorganization of atmospheric circulation with accompanying climate change, then a major change in biome systematic composition occurs.

The climate extremes at which intensified vegetational turnover would be expected include a shift to aseasonal conditions, such as ever-wet or perhumid (precipitation for 12 months/year) or arid (0 months/year) (Cecil, 2003). Unfortunately, there is a very low probability for preservation of identifiable macrofloral remains at these extremes (DiMichele and Gastaldo, 2008). Where seasonal variation is minimal under humid (9–11 months/year) or semi-arid (1–2 months/year) climate, one might expect a macrofloral record to be preserved in the former, but not the latter conditions (DiMichele and Gastaldo, 2008). Under relatively constant conditions in a humid climate belt, persistence would be the normal vegetational (biome) response. Under medial (6–8 months/year) to maximum (3–5 months/year) seasonality, a higher proportion of taxa experience protracted conditions that stress and ultimately exceed their physiological envelope.

The fact that systematic replacement across the Enna Marine Zone is concentrated in taxa centered in mineral-substrate soils would imply a change in conditions to greater seasonality across the landscape. If the coastal areas along the margin of the Upper Silesian Basin had become wetter (aseasonal) during the extended interglacial, then systematic persistence would have prevailed and there would not have been a significant turnover in taxa at this point in time. Such a pattern is witnessed in all preceding and subsequent cyclothem clusters (Gastaldo et al., 2009). Hence, a shift to greater seasonality where rainfall patterns may have been more monsoonal in nature (concentrated periodic rainfall punctuated by months of dryness) would account for not only physiological stresses resulting in the extinction-extirpation pattern identified at the Hrušov-Jaklovec boundary, but also the requisite sediment supply to fill marine accommodation space (Cecil and Dulong, 2003; DiMichele and Gastaldo, 2008).

CONCLUSIONS

The deposition of a stratigraphic interval exceeding 200 m in thickness in which only fully marine genetic sequences occur records a far-field record of Serpukhovian deglaciation. The thick Enna Marine Zone, marking the boundary between the Hrušov and Jaklovec Members of the Ostrava Formation, Czech Republic, is interpreted to represent sedimentation in a series of punctuated rises in eustatic sea level, each bounded by a maximum flooding surface, that developed in response to southern hemisphere deglaciation in the late Serpukhovian (e.g., Limarino et al., 2002; but see Isbell et al., 2003, who contend that there was insufficient Gondwanan ice buildup during Glacial II to cause a major sea-level rise upon melting). Although other thick marine sequences mark boundaries in other parts of the Ostrava Formation (e.g., Barbora Marine Zone,

boundary between the Jaklovec and Poruba Members), the petrophysical character of rocks in distal parts of the basin indicates the prevalence of one or two genetic sequences. Such a signature without the presence of a discrete MFS indicates that these intervals are equivalent in duration to other identified cyclothems (Gastaldo et al., 2009).

The consequence of Gondwanan deglaciation influenced the paleo-equatorial climate, shifting it from aseasonal and humid (during which times economic coals accumulated in a cyclothemic framework) toward one in which greater seasonality prevailed. Ecological perturbation occurred in the terrestrial landscape as individual physiological thresholds were crossed, resulting in a statistically significant turnover in coastal plain taxa (Gastaldo et al., 2009). Plants comprising wetland assemblages (Flöznahe of Havlena, 1961, 1971; Gastaldo, 1996) did not disappear, but were probably reduced in their biogeographic range to refugial wet sites where they continued to thrive. In contrast, taxa centered in mineral-substrate soils (Flözferne assemblages) were affected by the climatic change, with extinctions or extirpations in all clades. Inasmuch as both groundcover and liana taxa (lycopsids, sphenopsids, pteridophytes, and gymnosperms) and understory shrubs and trees (pteridophytes, gymnosperms) were impacted over the duration of the Enna Marine Zone (but not elsewhere in the section), a climate shift to everwet (aseasonal) conditions is not envisioned as the controlling climate disturbance. Such a shift would not have impacted these taxa because they were part of the Serpukhovian landscape in older coal-bearing cycles. Rather, individual systematic responses to conditions promoting physiological stress affecting growth and reproduction, such as shorter seasonal rainfall and longer periods of drier conditions and warmer-hotter temperatures (e.g., monsoonal rainfall), would have been the primary factor responsible for population demise. Similar patterns of extinction are recorded in the marine realm for the late Serpukhovian, suggesting a linkage between the effects recorded in both the terrestrial and marine records.

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