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Late Carboniferous tectono-sedimentary evolution and related terrestrial biotic changes on the North Variscan and Appalachian forelands, and adjacent paralic and continental basins

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Станислав Оплуштил — Позднекарбонская тектоно-седиментологическая эволюция и связанные с ней сухоземных биотических изменений в Северноварисском и Аппалачском флорандах и в соседних паралических и континентальных бассейнах. Сделана общая характеристика пенсильванского климата, палеогеографии, тектонических процессов и изменений сухоземных биот. Они анализированы на основании многочисленных опубликованных данных. Приведены также данные о геотектонической и палеогеографической позиции и о тектоно-седиментационной эволюции основных бассейнов Евроамериканской угленосной провинции, а также — данные о характере отложений в этих бассейнах в конце вестфалья и начале стефана. Обсуждены возможные контролирующие факторы, которые привели к изменению растительности и к ограничению и исчезновению углеобразующих лесов. Судя по литературным данным среди этих факторов самыми важными являются глобальные климатические изменения и тектонические процессы вариссийского орогенеза, в результате которых уменьшилась скорость погружения и наступила инверсия бассейнов. Важным фактором, который привел к палеогеографическим изменениям, было образование Пангеи и соответствующих орографических барьеров, которые оказали существенное влияние на процессы ускорения — размещения и на процессы континентального дрейфа поперек экваториальных климатических поясов. Так как перемещенные процессы происходили одновременно, конечный эффект их влияния на сухоземный биоценоз являлся по всей вероятности результатом их комплексного взаимодействия. В Северной Америке самые важные каменноугольные бассейны с более или менее полной геологической записью седиментационных процессов, проходящих через вестфаль-стефанскую границу являются: Западный и Восточный Интериор, Аппалачский бассейн и бассейн Канадского побережья. Они были интерпретированы соответственно как бассейны кратона, флоранда и как бассейн, обусловленный сдвиговыми движениями. В Европе эту границу можно проследить начиная с Южного Уэльса и угольных бассейнов Верхней Силезии (Северный вариссийский фор-

Abstract. The general characteristics of the Pennsylvanian climate, palaeogeography, tectonic processes and changes of terrestrial biotas are analysed based on an extensive set of published data. Data are also presented on the geotectonic and palaeogeographical position, as well as the tectono-sedimentary evolution of the main basins across the Euramerican coal province, and the character of the strata around the Westphalian – Stephanian boundary in these basins. Controls potentially responsible for floristic changes and the decline of the coal measures forests are discussed. Among those which have appeared in the literature, the most important are global climate change, tectonism related to the Variscan Orogeny resulting in a decrease of subsidence rate and onset of basin inversion, palaeogeographical changes related to the formation of Pangea producing orographic barriers that affected precipitation-distribution and continental drift through the latitudinal climate belts. Since all these processes operated simultaneously, the final effect on terrestrial biotas is most probably the result of an interplay of all these controls. In the North America, the most important basins with a more or less complete sedimentary record across the Westphalian – Stephanian boundary are the Western and Eastern Interior Basins, the Appalachian Basin and the Canadian Maritimes Basin, which have been interpreted as cratonic, foreland and strike-slip basins respectively. In Europe, this boundary is recorded from the South Wales and the Upper Silesian Coal Basins in the North Variscan foreland and from adjacent continental basins (Saar-Lorraine, basins of the Bohemian Massif and South Carpathian area, and the Dobrudzha Basin located on the Moesian Platform). Different palaeogeographical and geotectonic positions of the basins provide an excellent platform for comparison of common and specific features in sedimentary and palaeontological records, and consequently the identification of the most important controls operating in each basin. Finally, it may allow us to identify the main mechanism responsible for the decline of tropical mires and the accompanying floristic changes.

ланд), через соседние континентальные бассейны (Сарско-Лотарингский, Южнокарпатские бассейны и бассейны в Богемском массиве) и в Добруджанском бассейне на Мизийской платформе. Разнообразие в палеогеографической и геотектонической позиции всех этих бассейнов является великолепной основой для сравнения общих и специфических особенностей седиментационной и палеонтологической записи, а также — для выявления тех самых важных факторов, которые контролировали развитие каждого из бассейнов в частности. В итоге это дает нам возможность выявить основные механизмы, которые привели к сильному ограничению территорий, занятых тропическими болотами и к соответствующим изменениям растительности.

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Introduction

The end of the Westphalian in the Euramerican coal province is marked by the beginning of collapse of the coal measures forests, which for more than 10 My since the middle Namurian had dominated the tropical lowland areas. The end of this spectacular ecosystem resulted in a significant decrease in coal deposits, marked especially in the paralic basins of the north Variscan and Appalachian forelands. The decline of this ecosystem was accompanied by significant floristic changes, the most prominent of which was the sudden decrease of arborescent lycophytes, which had dominated the Namurian and Westphalian tropical wetlands of Euramerica (DiMichele and Phillips, 1994), and their replacement by more adaptable plants of the early conifers and particularly of the tree ferns (Marratiales) around the Westphalian/Stephanian boundary. This floristic change is generally ascribed to the onset of greenhouse conditions, the counterpart of the icehouse climate which, at the end of the early Namurian, had resulted in Gondwana glaciation, and worldwide regression and the consequential rapid spreading of wetlands over the newly-exposed extensive coastal lowlands (e.g. Wagner, 1993; Pfefferkorn, 2000). As with this icehouse period, the onset of greenhouse climate from the beginning of the Stephanian is still not fully understood, and both events are ascribed to various controls ranging from processes often related to the Variscan Orogeny and the formation of Pangea. Despite the variety of opinions, it is, however, widely accepted that the Stephanian is characterised by the gradual warming which culminated in the Late Permian and Early Triassic (Rowley et al., 1985) and is

in most areas marked by predominantly red-bed deposits with a scarcity or absence of organic matter. The greenhouse climate at the end of the Palaeozoic is also responsible for a general retreat of spore-producing plants and of amphibians requiring wet habitats for the successful completion of their life cycle, and their replacement by seed plants (mostly conifers) and by reptiles adaptable to drier conditions.

General characteristics of the Pennsylvanian

The Late Carboniferous was one of the most dynamic periods of Earth history. The amalgamation of a single large super-continent, Pangea, was accompanied by severe tectonic processes as well as mountain- and basin-formation related to the Variscan Orogeny. By the Late Carboniferous the main collisional processes were past their peak, but they nevertheless still significantly affected the tectono-sedimentary history of most basins as indicated by the onset of basin inversion and folding of the North Variscan Foreland Basin and by frequent hiatuses in the sedimentary record of most continental basins. These processes also had a profound effect on base-level changes and, consequently, on the intensity of drainage or water table fluctuation. They thus controlled the character of the flora and drove the alternation of wetter (e.g. peat forming) or drier ecosystems related to poorly- or well-drained substrates. The collisional processes related to the Variscan Orogeny and Pangea formation resulted also in the raising of orographic barriers which affected atmospheric circulation and moisture distribution. Moreo-

ver, northward drift of the Pangaea shifted the Euramerican floristic province from an equatorial position during the Late Carboniferous to higher latitudes with drier climate in the Permian.

Tectonic processes related to the Variscan Orogeny also coincided with climatic changes, which are considered to be global in character. The first of them is marked by global cooling and Gondwana glaciation in the early Namurian, whereas the second one started by gradual warming around the Westphalian – Stephanian boundary. Both had a profound effect on the character and distribution of existing terrestrial ecosystems.

The Variscan – Appalachian orogenesis

The two main continents, the Old Red Continent (Laurentia-Baltica) to the NW and Gondwana to the SE, together with a number of small continental plates intercalated between them (e.g. the Armorican Terrane Assemblage), gradually came together towards the end of the Early Palaeozoic, resulting in the single giant continent, Pangaea (Scotese and McKerrow, 1990). This diachronous and very complex process of collision and amalgamation, known as the Variscan Orogeny in Eu-

rope or the Appalachian and Ouachitas Orogenesis in North America, formed a large (c. 1,000 km wide and 8,000 km long) Himalaya-scale mountain system extending from the Caucasus to the Appalachian and Ouachita mountains in North America (Matte, 2001), following approximately the equator of the time. The main processes of continental collision related to the Variscan Orogeny spanned the interval of the Early Carboniferous and gradually diminished during the Late Carboniferous. However, in detail it consisted of a series of more or less local or regional processes, called phases, lasting for several tens of thousand to more than one million years, as inferred from the estimated length of the hiatuses in the sedimentary record of those basins with strong tectonic influence. These phases might be a response to local collisions and amalgamation of small terranes producing their own fold belt (Matte, 2001).

The Variscan mountain belt is often compared to Himalaya-scale mountains, both in height and size. Compressional processes during the Early Carboniferous and isostatic compensation in the Stephanian and Early Permian are believed to be responsible for the several thousand metres high

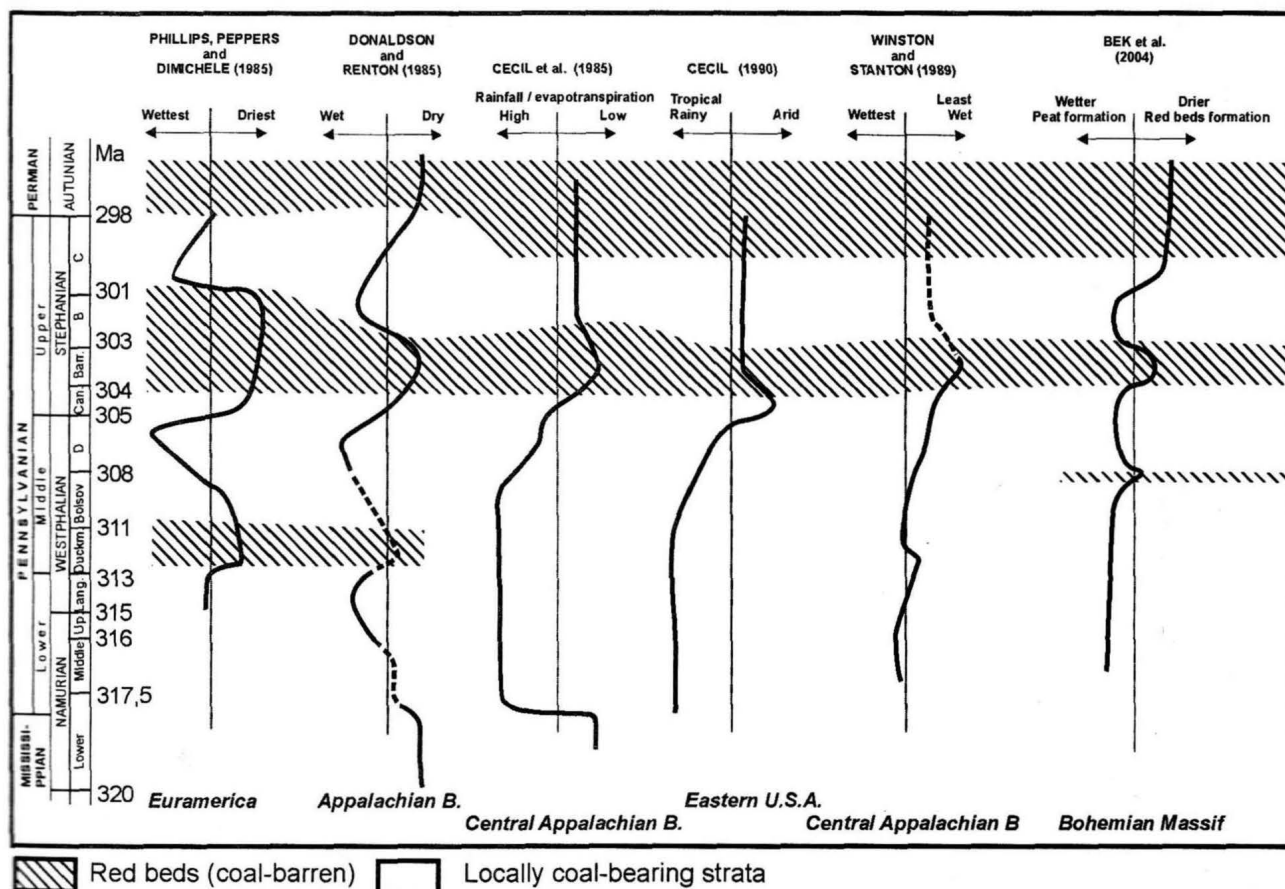


Fig. 1. Interpreted Pennsylvanian climatic trends for the Euramerican coal province, interpreted from floristic, palynological and sedimentological records

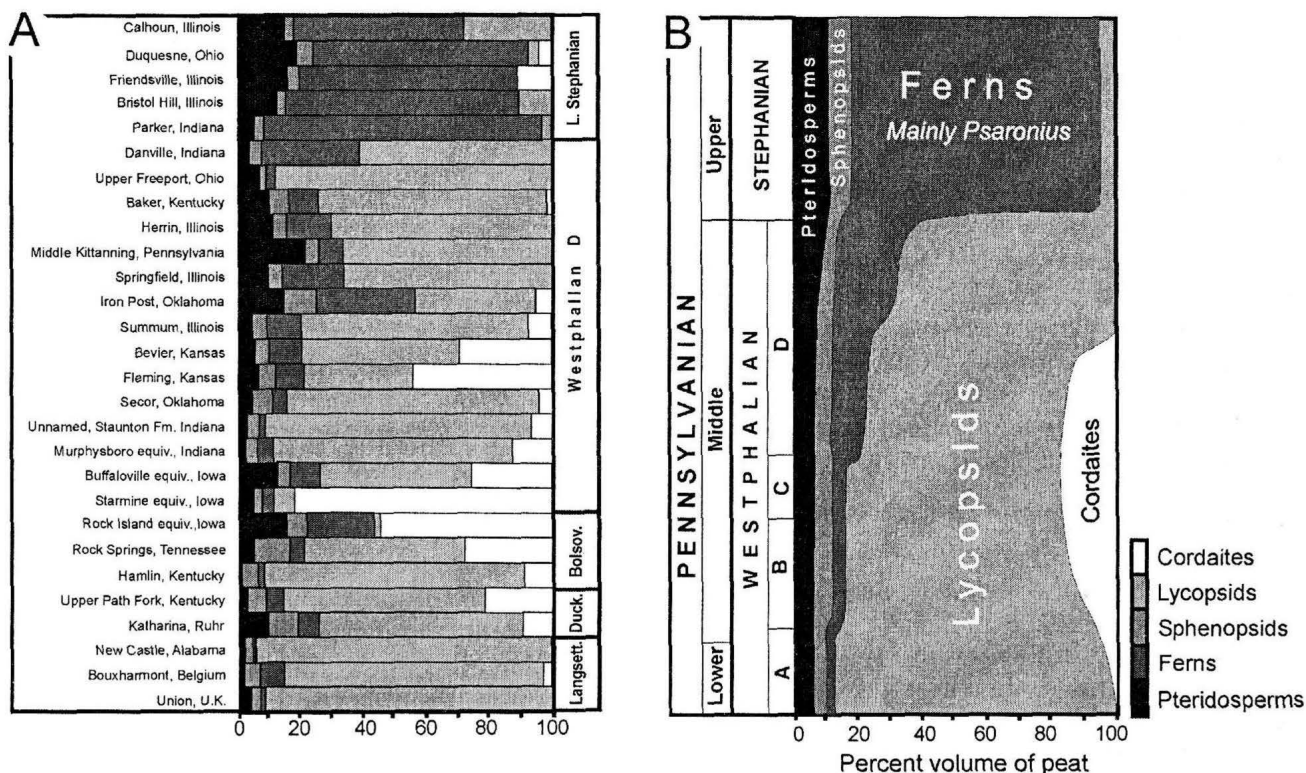


Fig. 2. A, Plant composition of selected Pennsylvanian coal seams of Euramerican coal basins based on coal-ball data; B, Interpretation of floristic changes during the Pennsylvanian with the main extinction around the Westphalian – Stephanian boundary (after DiMichele and Phillips, 1994)

mountainous topography of the Variscan fold belt. Altitudes proposed by various models or inferred from the sedimentary record vary between 4,000 m and 5,500 m above sea level (Mattaue, 1986; England and Houseman, 1989; Becq-Giraudon et al., 1991). It is often accepted that the altitude of the Variscan mountains gradually decreased due to rapid erosion of the quickly-rising orogene. As a result, Variscan granitoids and highly metamorphosed rocks originating from depths of more than 20 km were uplifted and exposed already in the Late Palaeozoic and served as the source-areas for many sedimentary basins. Thus the continental basins of the Bohemian Massif overlie the basement, which consists of Late Proterozoic and Early Palaeozoic folded sediments, and various crystalline rocks penetrated by Variscan granitoids. The basement of the late Stephanian – Early Permian Blanice Graben consists of high grade crystalline rocks metamorphosed during the Variscan Orogeny at depths of about 30 to 35 km (Schulmann, pers. com.).

The Pennsylvanian Climate

It is widely accepted that the Pennsylvanian was a period of climatic transition. The end of the Mississippian and onset of the Pennsylvanian is marked by global cooling (beginning of icehouse climate) related to Gondwana glaciation (Crow-

ell, 1978; Heckel, 1986; Veevers and Powell, 1987). It reached its peak during the Middle Pennsylvanian (DiMichele et al., 1996) and declined in the Early Permian, being followed by a warming trend (greenhouse climate) which continued into the Mesozoic (Fig. 1). The onset of transition from the icehouse to the greenhouse climate was characterised by drying, the first signal of which falls at the end of the Westphalian and beginning of the Stephanian. In the sedimentary record, it is marked by a decrease in coal deposits, the formation of red-beds, and floristic changes (Fig. 2) characterised by the transition from the Westphalian, lycophyte dominated assemblages to the Stephanian ecosystem rich in ferns and early seed plants (including pteridosperms, cordaites).

In general, the Early and Middle Pennsylvanian climate of the Euramerican coal province is considered to have been generally humid, ranging from ever wet to seasonally wet (Rowley et al., 1985; Calder and Gibling, 1994) which in lowlands favoured the development of lycophyte dominated plant ecosystems. It coincides with the general absence of annual growth rings (e.g. Phillips et al., 1985; Falcon-Lang, 1999). Such a climate persisted until the end of the Middle Pennsylvanian, when it started to change to warmer and relatively drier conditions. This transition to a greenhouse climate is characterised by a series of

alternating wetter to drier pulses, with each drier interval becoming more severe than the previous one, whereas wetter intervals tended to be gradually shorter and less prominent. This trend becomes first apparent around the Westphalian – Stephanian boundary and grades during the Stephanian (Gastaldo et al., 1996), and is manifested by the alternation of ‘grey’ coal-bearing and red coal-barren strata. Good examples are provided by the Late Palaeozoic continental basins of the Bohemian Massif in the Czech Republic and the Appalachian Basin in North America. All these basins are characterised by a sudden decrease in the number of coal seams in the lower and upper Stephanian, separated by a middle Stephanian coal-bearing episode (Rowley et al., 1985). The length of these climatic cycles varies around 1My. It is a much longer periodicity than the orbitally-driven climatic pulses known as Milankovic cycles, the length of which is inferred to be at the scale of a few tens to the low hundreds of thousand of years. These cycles are considered to be responsible for the generation of coal-bearing cyclothems during the Namurian and Westphalian (e.g. Wanless and Shepard, 1936; Calder and Gibling, 1994; Heckel, 1995, 2002).

Coal measures forests; onset, culmination and declining

The most characteristic feature of the Early and Middle Pennsylvanian tropical lowland ecosystems were coal measures forests, which produced the coal seams of the Euramerican coal belt, and were dominated by spore-producing plants, especially by tree lycophytes which produced about 90 – 95 % of the biomass (DiMichele and Phillips 1992). Their onset occurred already by the end of the Early Carboniferous (Mississippian) but at that time were restricted to only a few basins (e.g. the Midland Valley in Scotland, the Upper Silesian Basin, the Donetz Basin) in which thick economical coal seams are present. However, the real expansion started at the beginning of the Pennsylvanian with the onset of the icehouse climate. It led to the worldwide regression exposing vast areas of coastal lowlands, which provided suitable conditions for the development of wetlands. The wet and tropical climate favoured colonisation of these habitats by extensive peat-forming mires which spread over the whole area of the Euramerican coal province until the end of the Namurian. At its maximum extent, these tropical coal measures forests covered a more or less continuous area of about 4 million km² of Europe. However, together with North America and China (North and South China), the total area is estimated to be about 8 million km². This terrestrial

ecosystem dominated tropical wetlands of Euramerica until the end of the Westphalian when it started to decline. By the Early Stephanian, they had disappeared from Scotland and most of the Pennine Basin, as well as from most areas of the North Variscan Foredeep. They persisted only in South Wales, Upper Silesia, Donetz and Dobrudzha and Zonguldag basins, and had but disappeared from here by the end of the Early Stephanian (Barruelian). During the middle and late Stephanian, they survived only in the Appalachians and a number of continental basins of the Variscan interior, including the Saar-Lorraine, Central France and Armorican Massifs, the Iberian Massif, the Bohemian Massif, as well as in basins located within the southern flank of the Variscan Orogen and its foreland. In these basins, infrequent but locally very thick economical coal seams occur until the top of the Carboniferous or the lowermost Autunian, when they definitely disappear from Euramerica. During the Permian, lycophyte-dominated tropical coal measures forests persisted only in North and South China (Liu 1990), far distant from the main Pangaea landmass and the tectonic processes related to the Variscan Orogeny.

Major coal basins of the Variscan and Appalachian forelands and adjacent areas

Tectonic processes related to various phases of the Variscan and Appalachian Orogenesis generated a number of sedimentary basins of different tectono-sedimentary histories, controlled mainly by the rate of subsidence, eustasy, sediment influx and climate (Fig. 3). Depending on their geotectonic position, these basins can be subdivided into (1) foreland basins (e.g. Appalachian Basin and North Variscan Foreland Basin); (2) cratonic basins (Eastern Interior, Pennine, Campine, Southern North Sea and Lublin Basins) and (3) fault-related (strike-slip or extensional) basins. Within each group, different mechanisms controlled basin subsidence and consequently thickness and character of sedimentary record. Here, only those basins with a sedimentary record of the Upper Westphalian and Lower Stephanian strata are discussed.

Foreland basins

These basins form in a compression regime of collision zones along the plate margins by tectonic load of one plate over the other. Subsidence is produced by down-flexure of the lithosphere due to tectonics, and latter also by sediment load, generating accommodation space for thick sedimentary sequences. Sediments of these basins are in-

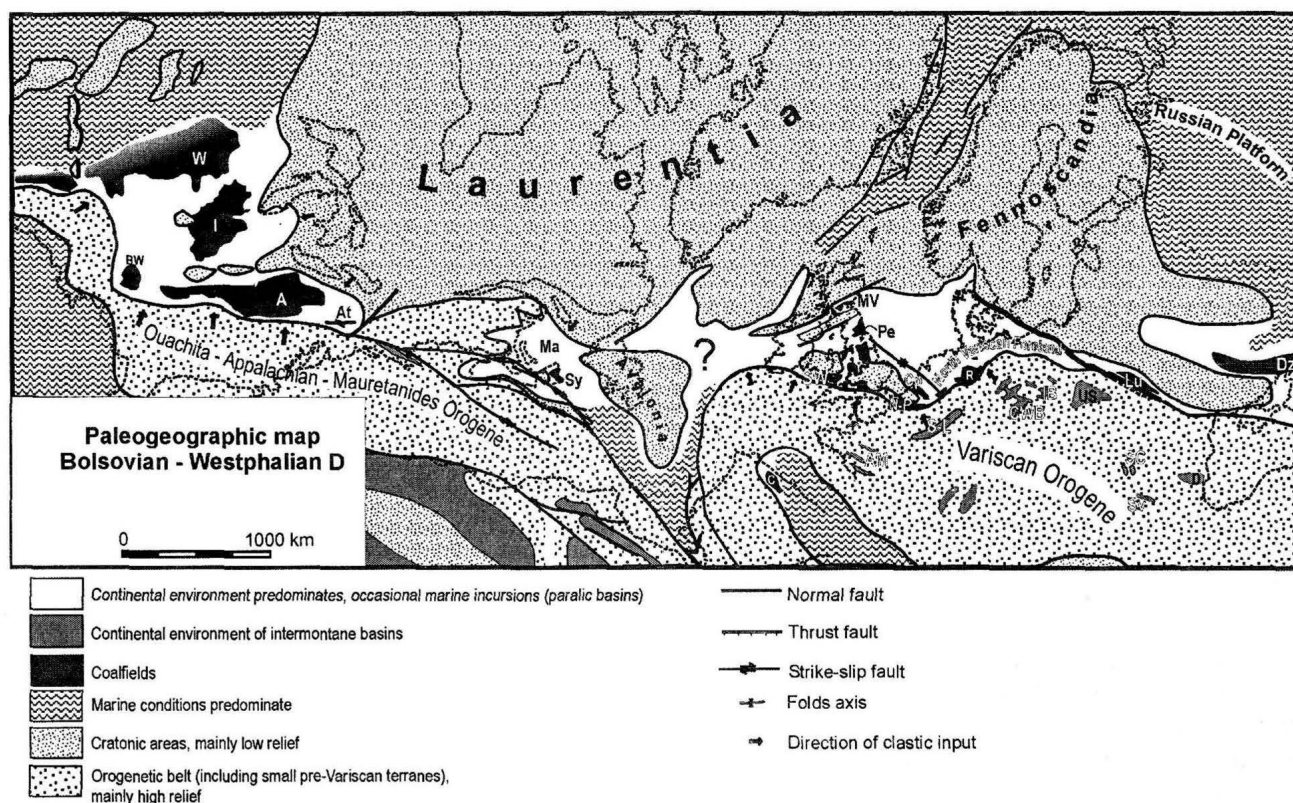


Fig. 3. Palaeogeographical map of Euramerica at the end of the Westphalian. Based on Ziegler (1990), modified by data of Calder (1998), Pešek et al. (1998), etc. Basins or coalfields: W – Western Interior; I – Illinois; A – Appalachian; BW – Black Warrior; At – Anthracite Coalfield; Ma – Maritimes Basin; Sy – Sydney Coalfield; MV – Midland Valley; Pe – Pennines; SW – South Wales; N-P – Pas-de-Calais, Nord and Namur Coalfields; Cp – Campine; R – Ruhr; Lu – Lublin; Dz – Donetz Basin; AM – continental basins of Armorican Massif; S-L – Saar-Lorraine; CWB – central and western Bohemia; IB – Intra Sudetic Basin; US – Upper Silesia; SC – South Carpathian basins; Sv – Svoje Basin; D – Dobrudzha Coalfield

tensively folded and thrust due to tectonic compression. Consequently, coals of these basins are usually highly coalified with intensity decreasing away from deformation front. Stratigraphy in these basins is controlled by tectonics, sedimentary influx and by eustasy. However, eustatically controlled cyclothems are usually overprinted by stronger tectonic influence. Thus, within a single eustatic event local tectonic activity can cause the appearance of several apparent 'cycles' (Drummond and Wilkinson, 1993). Consequently, stratigraphic sequences of foreland basins are not simply correlatable with those in cratonic basins, where most accommodation space is produced by thermal subsidence. Very good examples are provided by the clastic cyclothems of the Appalachian Basin in comparison with the mixed carbonate – clastic cyclothems of the Western and Eastern Interior Basins.

In the area being considered in this paper, there are two foreland basins: the Appalachian and the North Variscan Foreland Basin.

Appalachian Foreland Basin. This formed along the northern foreland of the Appalachian

mountains, following the collision zone between Laurentia and the African margin of Gondwana. A formerly continuous sedimentary area is now divided by subsequent erosion and tectonics into several isolated parts, the largest of which is the Appalachian Basin with its southern protrusion, the Black Warrior Basin, and the Anthracite Coalfield to the north-east. In these basins, Mississippian carbonates are overlain by thick coal-bearing sequence of clastic-dominated strata of Pennsylvanian age.

Palaeogeographically, the Appalachian basin communicated with epicontinental sea located further to the north-west on the North American Craton. This communication resulted in frequent, short-lived marine incursions. As a result, widespread marine bands provide an excellent tool for correlation over the whole basin. Some of them are believed to be correlatable with the major marine bands of the North Variscan Foreland in Western Europe (Blake et al., 2002). However, in the Appalachians, the marine incursions occur up to the level of the Conemaugh Group of 'early' Stephanian age whereas in the North Variscan Foreland the youngest marine band is in the middle Bolsovian.

It was believed that the Appalachian Basin provides a continuous profile through the whole Pennsylvanian. However, recently Wagner and Lyons (1997) postulated a multi-million-year discontinuity in the lower part of the Conemaugh Formation (approximately at the Middle and Upper Pennsylvanian boundary) between the Mahoning and Mason coal seams, based on disruption in floristic succession. Nevertheless, palynological (Peppers, 1996, 1997; Kosanke and Cecil, 1996) as well as invertebrate data (Heckel, 1994) do not support the presence of more than a minor hiatus at the level of *Lycospora*-producing lycophyte extinction (Blake et al., 2002). This stratigraphic level also coincides with the onset of red-beds strata containing only very few coal seams. A new increase in frequency of coal seams occurs in the succeeding Monongahela Formation of middle Stephanian age, where a number of important coal seams (e.g. Pittsburgh, Sewickley or Waynesburg) occur.

North Variscan Foreland Basin. This developed as a system of peripheral foreland basins along the northern margin of the Variscan Orogen, and was related to the collision of peri-Gondwanian terranes (e.g. Armorican terrane assemblage) with Baltica (eastern part of Laurussia) on the north. Coal-bearing strata are predominantly of Early and Middle Pennsylvanian age, with a few exceptions of Late Mississippian age (Upper Silesian Coal Basin). They crop out only along the southern margin of the basin, as further north they are mostly concealed under the thick sequences of younger sediments. They are arranged into a discontinuous belt of coalfields arranged here from west to east: South Wales, Forest of Dean, Bristol – Somerset, Oxfordshire-Berkshire, East Kent, Northern France (Pas-de-Calais and Nord), Namur, Aachen, Ruhr and the Upper Silesian Coal Basin. To the north, with increasing distance from the fold belt, intensity of deformation and coal rank decreases. The North Variscan Foredeep grades northward into paralic basins (e.g. Pennine, Campine, Southern North Sea and Lublin), which are located on stable basement and are thus rather of cratonic position.

Due to differences in subsidence rate or as a result of post-sedimentary denudation, the thickness of coal-bearing Pennsylvanian strata of the North Variscan Foredeep varies strongly in individual coalfields, between several hundreds of metres (erosional thickness) to more than 4,000 m in the Upper Silesian Coal Basin.

Sedimentary fill of the North Variscan Foreland Basin is characterised by considerable continuity of strata over a distance of several hundred kilometres. Nevertheless, pronounced differences in

the lithological composition, stratigraphical range of succession, thickness, and numbers of marine horizons indicate that N–S striking tectonic elements separated distinct areas of the foreland and played an essential role in the palaeogeographical development (Franke, 1990). Several peaks of the orogenic collisional movements within the Variscan external zone (called phases or events) are reflected in the foreland by the northward migration of depocentres. They are also marked by breaks in sedimentation and denudation processes marked by erosional discordances or even weak angular unconformities or by changes in lithological and architectonic character of sedimentary fill. The most important events are related to the Upper Namurian and Upper Westphalian.

The most economical coal seams are of the late Langsettian and Bolsovian age. Coal-bearing strata of the Westphalian D and Cantabrian age are preserved/developed only locally, especially in the South Wales and Bristol Somerset Basins, and the small satellite coalfield of the Forest of Dean. A possible earliest Stephanian age is also inferred for the youngest coal seams of the Libiaz Member of the Upper Silesian Coal Basin (Cleal, pers. com.). In other coalfields of the North Variscan Foredeep the youngest coal seams are probably of the Westphalian D age. Middle to upper Stephanian deposits rest on Westphalian strata with erosional discordance. Their mostly brick-red colour indicates either drier climate or falling base level resulting in development of well-drained alluvial plain.

Palaeogeographically, the basin developed as an extensive coastal lowland in front of the Variscan Mountain chain, with paralic deposition from the Langsettian to Duckmantian and locally to the lower Bolsovian (South Wales). Gradual shift from a more marine-influenced environment in the Namurian – early Westphalian, to more continental settings in the late Westphalian – early Stephanian is evidenced by the decreased frequency of marine incursions in the younger strata. Pedological and sedimentological evidence indicate increased aridity towards the end of the Westphalian (e.g. Besly, 1988). In the late Namurian – early Westphalian, mudstone-dominated lower delta plain setting with large interdistributary areas separated by low gradient meandering channels dominated most parts of the North Variscan Foreland. During the late Langsettian and early Duckmantian, transition took place to more continental upper delta plain setting dominated by meandering to anastomosed rivers with broad alluvial plains. In the Bolsovian, a purely fluvial setting was established. In most places sand to gravel dominated braid plain developed during the Bolsovian and persisted until the end of deposition in

the Westphalian D or early Stephanian, probably as a response to increased sediment input due to proximity of an emerging Variscan mountain belt and the high gradient imposed by local tectonism (Dreesen et al., 1995).

A different scenario exists in the Upper Silesian Coal Basin, where the Lower Namurian, highly coal-bearing paralic deposits are terminated by a depositional break, and are followed by a middle Namurian (ex Namurian B) to early Stephanian, purely continental coal-bearing succession, up to 4,000 m thick. Its deposition, controlled mainly by local tectonic processes, is characterised by an alternation of sandstone- and mudstone-dominated units which indicate changes in intensity of tectonic regime. The youngest unit, the Cracow Sandstone Series (Bolsovian – lowermost Stephanian ?) was deposited within a braided fluvial system (Gradzinski et al., 1995) and is lithologically similar to the Pennant sandstone of the South Wales Coalfield.

Rift and cratonic basins

These genetically related basins developed on consolidated parts of plates (cratons) by tectonic processes related to extension, later grading into thermal subsidence produced by cooling of the lithosphere that had previously been heated during the initial phase of continental rifting. Relatively low and even subsidence rate of cratonic basins are accompanied by weak tectonic activity due to their location away from the orogenic belts, and these factors allow ideal condition for the development of climatically-driven cyclothems. Hiatuses are uncommon but, if present, they are often related to eustatically driven drops in sea-level.

Thickness of strata of cratonic basins is usually low in comparison to the foreland basins. Horizontally to sub-horizontally lying strata are only occasionally interrupted by normal faults. The typically low rank of coalification in these basins makes them particularly suitable for palynological and cuticular studies. The weak tectonic activity and clastic input in these basins probably provide the best opportunity to study the effect of climatic changes on biotas and sedimentary record.

Examples of these basins are the Interior and Michigan basins in North America; the Pennine, Campine basins and Midland Valley (? rift basin) in western Europe; and the Lublin Basin developed on the western margin of the Russian Platform.

Eastern (Illinois) and Western Interior (Midcontinent) Basins. These basins are located on the North American Craton west of the Appalachian Foreland Basin, possibly with some tectonic in-

fluence from the adjacent Appalachian fold belt. They contain both Mississippian and Pennsylvanian strata separated by an erosional surface related to the early Namurian lowstand. Paralic, locally coal-bearing Pennsylvanian strata range from the Langsettian to the Stephanian (Fig. 4), with maximum coal content concentrated in the Westphalian D (Upper Desmoinesian). These strata are arranged into cyclothems, with marine bands composed of carbonates and shales deposited on a low-gradient shelf or ramp with little relief (Nelson et al., 1991). This palaeotopography permitted sea-level changes to affect large areas of the craton, thus producing basin-wide cyclothems. The higher, Stephanian cyclothems are rich in marine sediments but contain mostly thin coal seams of only minor economical importance.

The Illinois Basin is the area where cyclothems were first mentioned and described by Wanless and Weller (1932). In contrast to the Appalachian-type cyclothems, mid-continent-type cyclothems are carbonate-rich and thinner, with a lower proportion of continental clastics due to the flat extrabasinal topography. There is also weaker tectonic activity here in comparison to the fold-belt-bounded Appalachian Basin. The duration of individual cyclothems of the Illinois Basin is estimated to be 24–129 ky (Klein, 1990; DiMichele et al., 1996).

In the context of climatic changes, the limestone/coal couplets represent interglacial and glacial cycles of the Late Carboniferous cold interval, prior to the first major deglaciation (Frakes et al., 1992; Gastaldo et al., 1996). Each marine limestone represents an interglacial (i.e. sea-level highstand) that is characterised by a wet-dry tropical climate. Each coal or coal group (depending on splitting) represents a glacial cycle (i.e. sea-level lowstand) during which a tropical ever-wet climate prevailed (Cecil, 1990).

The palaeogeographical position of the basins along the western part of the Euramerican Floral Province, their considerable stratigraphical record, and the strong influence that climatic controls are thought to have on deposition, makes these basins especially important for the study of floristic changes around the Westphalian/Stephanian boundary.

Pennine Basin. This basin is located in the English Midlands from where it continues to the east under the North Sea and to the south to the North Variscan Foreland Basin. From the foreland basins of the southern part of the British Isles (South Wales Coalfield, Bristol – Somerset, Kent) it is separated by the London – Brabant Massif (Eastern Avalonia terrane), although, limited communication between the two basins was possible

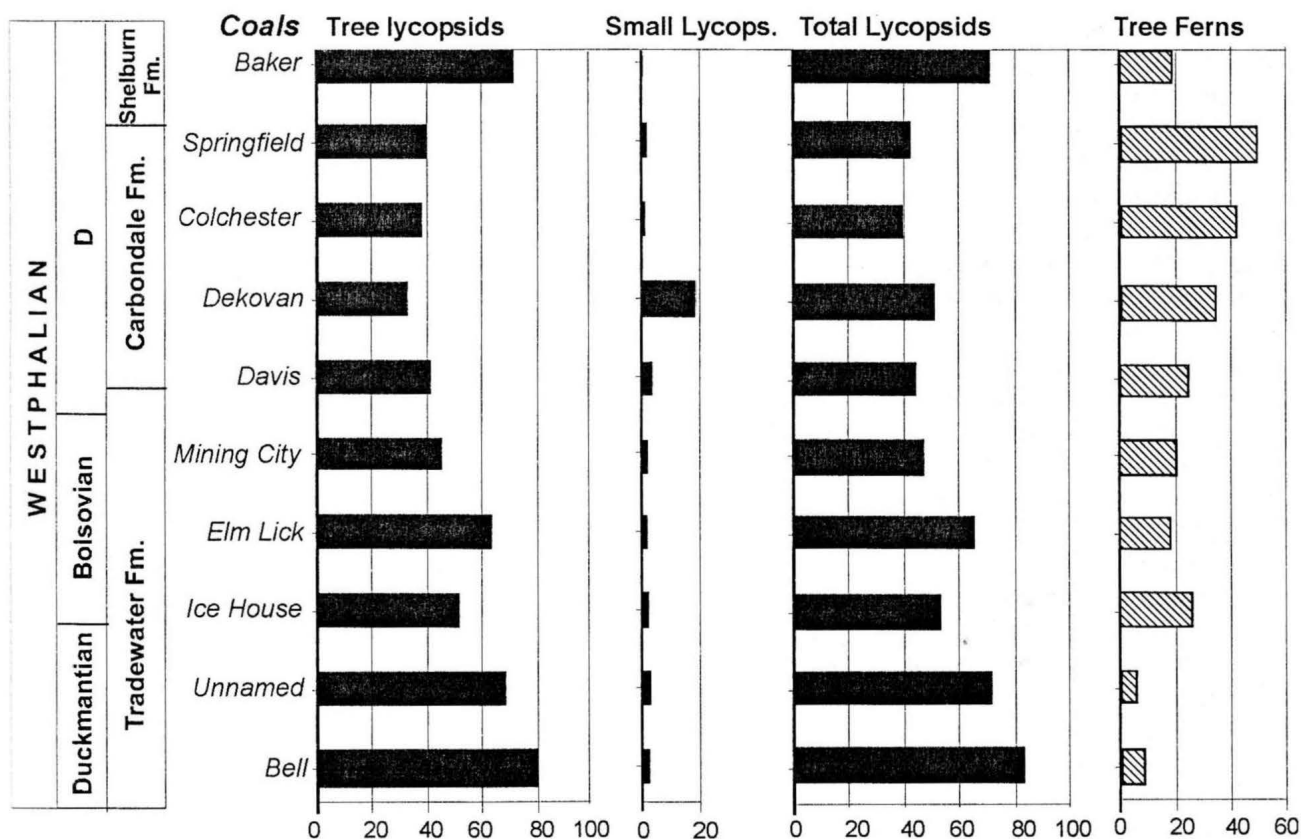


Fig. 4. Relative plant-abundances of selected coal seams of the Illinois (Eastern Interior) Basin derived from palynological data (prepared from data published by Eble et al., 2001 and Mahaffy, 1988)

through the Warwickshire and Oxfordshire Coalfields. During the Late Carboniferous, the Pennine Basin in central England was a thermally subsiding, intracratonic basin opened during N-S oriented extension (Read, 1988) with only little active tectonics. Its sedimentary fill consists of coarsening-upward deltaic cyclothems bounded by widespread faunally-concentrated condensed horizons (Hampson, 1995).

Coal-bearing strata of the Pennine Basin span the interval from the Langsettian to the Bolsovian. They were mostly deposited in a marine-influenced deltaic environment, but by the late Westphalian the marine influence declined and sedimentation took place in a purely fluvial setting (Guion et al., 1995). Most economic coal seams are concentrated in the middle Langsettian to upper Duckmantian interval and were formed when deposition in an upper delta plain setting favoured development of extensive mires. Marine influence is terminated by the Cambriense Marine Band in the lower Bolsovian. Coal-bearing strata pass diachronously up into red-beds of the Etruria Formation, which occurs at different stratigraphical levels in different parts of the basin. Red-beds facies are common, especially in the southern part of the basin where they form a diachronous complex ranging from the Langsettian to the Bolso-

vian directly adjacent to London – Brabant Massif (Besly, 1988). They formed in well-drained alluvial environments that coexisted with deltaic deposition further north in the Pennine Basin (Guion et al., 1995). During the Westphalian, the red-bed facies spread progressively northward, gradually replacing deposits of poorly drained deltaic environments, possibly as a consequence of tectonic uplift related to the Variscan Orogeny (Guion et al., 1995). Red-bed formation continued also during the Westphalian D and Stephanian, intercalated with only short episodes of poorly coal-bearing horizons in the uppermost Westphalian. Their palynological and macrofloral records indicate a Westphalian D age (Smith and Butterworth, 1967; Turner, 1994; Cleal, 1984; Besly and Cleal, 1997). Stephanian strata are palaeontologically very poorly documented and evidence of the presence of beds of this age is rather indirect, being based only on the superposition of beds above the Westphalian D sediments.

Lublin Basin. This is located on a stable basement on the southeastern margin of the Russian Platform, adjacent to the Variscan foreland with which it directly communicated. Consequently, this marginal cratonic basin was partly influenced from coeval Variscan tectonism. Mostly marine,

carbonate dominated Mississippian strata (Viséan) grade upward into a coal-bearing succession of Namurian to upper Westphalian age. Namurian to Langsettian sediments are in a paralic development with frequent marine bands. From the Duckmantian, the basin fill was purely of continental origin. Most coal-bearing strata occur in the upper Langsettian to Bolsovian part of the succession. The upper Bolsovian contains only few thin coal seams. The presence of Westphalian D sediments was identified palynologically at the top of the basin fill, but macrofloral data are rather poor. Sediments younger than early Westphalian D have not been detected.

Fault-related basins (extensional or strike slip basins)

Purely continental, fault-bounded basins are characterised by frequent hiatuses and by alternating red, coal-barren, and grey coal-bearing sediments. Their intra-continental position and higher altitude could result in different climate conditions (induced by orographic barriers etc.) and their partial isolation reduced the migration potential of plants. Consequently the flora of most continental basins exhibits higher numbers of endemic species.

Atlantic Canada Maritime Basins. These are a complex of predominantly northeasterly trending and formerly interconnected intermontane basins that lies within the northern Appalachians (Gibling et al., 1992; White et al., 1994; Calder, 1998). The basin fill spans the interval from the Devonian (Emsian) to the Permian, with only a few hiatuses. The Pennsylvanian episode of deposition took place in a strike slip setting (Plint and van de Poll, 1984) that changed at the end of the Bolsovian to thermal sag (Bradley, 1982). The total composite thickness of the Pennsylvanian strata reaches about 8 km (Hacquebard et al., 1960). Palaeogeographically, this basin complex was situated at the opposite side of the southeastern margin of the Appalachians, in contrast to the Appalachian Basin to the west (Calder, 1998). The mountain range formed an orographic climate barrier, a drainage divide, and a phytogeographical barrier to biotic exchange between the two regions. No such land barrier existed to the east, thus allowing the Maritimes Basin to communicate with basins in western Europe, especially in Great Britain (Calder, 1998).

Coal-bearing deposition in the Maritimes Basin is assigned to the Cumberland Group and is of Pennsylvanian age. During the Langsettian to Bolsovian, only aerially-restricted rheotrophic mires located in piedmont, intertributary or lacustrine settings developed (Calder, 1979, 1994).

Widespread mires developed from the Westphalian D to Cantabrian on upper coastal plain setting (Gibling and Bird, 1994) during the thermal sag. The resulting coal deposits represent the main economic seams of the basin. These coal-bearing strata are followed by the red-bed deposits of Stephanian to Permian age.

Saar-Lorraine Basin. This is the largest Late Palaeozoic continental basin formed within the European Variscides. Tectonically, it is located between the Rhenohercynian and Saxothuringian zones, following their SW-NE trending contact. It is a half-graben basin filled by Late Carboniferous to Permian strata. Up to 4000 m of Late Carboniferous coal-bearing strata span the interval from the Bolsovian to the Stephanian C, and consist of two parts: the Saarbrücken Group of Westphalian age, and the Ottweiler Group of Stephanian age. These Groups are separated by a prominent unconformity followed by the about 100 m thick Holz Conglomerate at the base of the Ottweiler Group. The duration of the hiatus has been discussed many times, but according to Laveine (1977) it comprises the latter part of the Westphalian D and the early part of the Stephanian. The intensity of erosion increases from southwest to the northeast, so the youngest Westphalian D strata are preserved in the French part of the basin (Laveine, 1977). Most of the economic coal seams are concentrated in the Westphalian strata. Stephanian sediments contain only a few coal seams and part of the succession is in red-bed development.

Erzgebirge Basin. This is located on the Saxothuringian basement, on the northern flank of the Erzgebirge Mountains in Saxony, and on the NW margin of the Bohemian Massif. It is now preserved as several isolated remnants, with the main one situated between the towns of Zwickau and Hainichen. The tectono-sedimentary history of the basin is very complex and starts already in the Early Carboniferous, and with several basin-wide hiatuses lasted until the Permian. Each of the sedimentary episodes represents different basin settings, from purely marine, to an alluvial environment in a piedmont setting. The Late Carboniferous is recorded in two units, the Flöha and Zwickau Formations, separated by a hiatus and developed in different, partly overlapping depocentres. The Flöha Formation is of the Bolsovian age and is considered to be a time equivalent of the Radnice Member in central and western Bohemia. It contains frequent volcanoclastic beds and rhyolite bodies (Pietzsch, 1956). Sediments are rich in arkoses, but also contain thin coal seams locally mined in the vicinity of Flöha. The following unit, the Zwickau Formation, is of Westphalian D age and consists of cyclically arranged strata with

frequent coal seams. These were mined in the Zwickau – Oelsnitz Coalfield until the 1970s and provided a very rich and diversified flora described by many authors (e.g. Daber, 1955). Stephanian strata are absent in the Erzgebirge Basin.

During the Westphalian, this basin was located palaeogeographically between the continental basins of the central part of the Bohemian Massif and the Northern Variscan Foreland.

Central and Western Bohemian Basins. These form the western part of the basin-system that continues further northeast across the Sudetic region to Poland. Both areas started as isolated depocentres, but merged into one large basin in the early Stephanian, when they spread over the Elbe Lineament zone separating the Bohemian Terrane with the Central and Western Bohemian Basins, to the southwest and the Saxothuringian and Sudetic Basins to the northeast.

The Central and Western Bohemian Late Palaeozoic basins are formally subdivided into several basins (Pilsen, Radnice, Kladno-Rakovník etc.) which were later partly isolated by post-sedimentary erosion, but originally formed within a single depocentre. The basins are interpreted by Pašek and Urban (1990) as a wrench fault system related to the main NW-SE trending faults. Sedimentary history in these basins began around the Duckmantian/Bolsovian boundary, and with several hiatuses lasted at least until the end of the Carboniferous. Basin-fill, the thickness of which reaches about 1400 m maximum, is divided into four lithostratigraphical formations based on alternating intervals of reddish, coal-barren, and greyish coal-bearing deposits (Weithofer, 1896, 1902; Pešek, 1994). Sedimentation in most of these basins started during the early Bolsovian with the deposition of the highly coal-bearing strata of the Radnice Member. This unit is separated from the overlying Nýřany Member by a basin-wide hiatus lasting from the late Bolsovian to the early Westphalian D. The Nýřany Member is about 300 to 500 m thick of mostly fluvial strata and spans the interval of the upper Westphalian D to the Cantabrian (Šetlík, 1977; Wagner, 1977), as indicated by the increasing frequency of occurrence of Stephanian plant elements such as *Sphenophyllum oblongifolium*. Economically important coal seams are located mostly in the lower part of the unit, with a few exceptions in the middle or even upper part of the unit. However, rich plant collections derived from coalfields and hundreds of boreholes represent all levels within this member. Sediments of this unit pass upward without any interruption into lithologically-similar fluvial strata of the Týnec Formation (Upper Cantabrian – Barruillian) which is a red-bed devel-

opment with poorly preserved rare plant debris (Šetlík, 1970).

Intra Sudetic Basin. This is located around the Czech – Polish border at the eastern margin of the complex of the Late Palaeozoic continental basins ranging from the western Bohemia in the Czech Republic to the ENE up to the Poland. The tectono-sedimentary history of the basin is very complex and spans the interval from the Devonian to the Triassic. Hiatuses are frequent. Mostly marine, Devonian to Early Carboniferous strata are followed by purely continental deposits comprising the remaining part of the fill. The whole thickness of the Late Carboniferous fill reaches about 2000 m. It is characterised by alternating red-beds and coal bearing grey coloured sediments. Economically important coal seams concentrate to two intervals. The older one range from the lower Namurian to the Bolsovian and the younger one from the Cantabrian to the Stephanian B. They are separated by a hiatus involving the upper Bolsovian and lower Westphalian D. A transitional succession from the Westphalian to the Stephanian is recorded in the Svatoňovice Member, the lower part of which consists of predominantly red-beds with only a poor flora indicating a Westphalian D age. The upper part of the unit (Upper Svatoňovice Member) contains the Svatoňovice Group of Coals, which have yielded very rich plant fossils of Cantabrian age (Šetlík, 1977; Pešek et al., 2001).

Late Palaeozoic continental basins of the Southern Carpathians. These comprise the Reșița and Sirina coalfields in southwest Romania, and each involves several half-graben basins: the Lupac and Secu Basins in the Reșița Coalfield, and the Dragosela, Baia and Cucuiova Basins in the Sirina Coalfield (Dragastan et al., 1997). Basin-fill consists mostly of fluvial strata represented by coarse-grained clastics, shales and coal. The thickness of Upper Carboniferous strata of particular basins varies from between 250 and 1000 m. The number of coal seams varies between two and ten (Dragastan et al., 1997).

Deposition in the Reșița Coalfield started in the early Westphalian (Langsettian) and continued until the Early Permian. The oldest strata, interpreted as alluvial fan deposits, grade upward into a Bolsovian to upper Westphalian D coal-bearing succession of fluvial origin (Nastaseanu et al., 1979). Similar deposition continued during the Stephanian after a short hiatus spanning the interval of the *Odontopteris cantabrica* Biozone, i.e. the lowermost Stephanian (Cleal, 1991; Dragastan et al., 1997) and assigned to the Asturian phase. Permian strata are deposited after another gap in deposition with the exception of the Lupac Basin

where continuous transition between the Stephanian and Autunian was observed (Dragastan et al., 1997).

Deposition in the Sirina Coalfield started in the late Duckmantian and continued till the end of the Carboniferous. Short hiatuses occur around the Westphalian/Stephanian and Stephanian/Autunian boundaries. The character of the sediments is comparable to that of the Reșița Coalfield. Coal-bearing strata are also of similar age.

These purely intramontane basins were located within the southeastern part of the Variscan Orogeny. Their former structures were later overprinted by the Alpine Orogeny. Consequently, the coal rank of these Upper Carboniferous strata is usually very high, unsuitable for application of maceration methods (Popa, pers. com.).

Dobrudzha Basin. This is located in northeastern Bulgaria on the Moesian Platform. Generally non-folded, sub-horizontally lying coal-bearing strata containing several tens of coal seams reach a thickness of more than 1100 m (cf. Tenchov, 1993). They span the interval from the upper Namurian (ex Namurian C) to the Cantabrian, but there are several short breaks in deposition. The transition between the Westphalian and the Stephanian is continuous and contains important coal seams.

Carboniferous strata of the basin are concealed under Mesozoic sedimentary cover and do not crop out. Therefore, all the available data are known only from deep boreholes. Basin fill is of purely continental origin, but palaeogeographically the Dobrudzha Basin was located not far from the northern margin of the North Variscan Foreland (Tenchov, 1989). Thus, it provides a link between the purely continental fault-bounded basins and the paralic basins of the North Variscan foreland.

Discussion

In the Euramerican coal province, the end of the Westphalian and onset of the Stephanian is marked by an apparent decrease in the frequency of coal deposits. This event is accompanied by floristic changes, among which the most prominent is the decline of the tree lycophytes and their replacement by tree-ferns. Changes in terrestrial biotas and the decline of the coal measures forests approximately coincide in timing with tectonic and palaeogeographic processes and climatic changes, which could be considered as the possible controls. Certain variations in scenario of these changes among individual basins indicate that the biotic changes and coal deposition retreat around the

Westphalian/Stephanian boundary are probably the result of an interplay of most of these controls, the intensity of which, however, varied stratigraphically and regionally across the Euramerican basins. To estimate which of them was or were the most important for a particular basin or for the province as a whole requires careful examination of the timing of the changes in each basin, and a precise correlation over the whole Euramerican coal province. This should allow us to distinguish local and regional from global features, and consequently to recognise the importance and role of particular controls, and to determine which one (if any) was the most important over the whole Euramerica and thus was the most responsible for the changes in biotas.

Several potential controls have appeared in the literature, among the most important being (1) global climate change, (2) tectonism related to the Variscan Orogeny resulting in decreasing of subsidence rate, and onset of basin inversion, (3) palaeogeographical changes related to the formation of Pangea producing orographic barriers that affected precipitation distribution, and (4) continental drift through the latitudinal climate belts. Since all these processes operated simultaneously, the final effect on terrestrial biotas is most probably the result of an interplay of all these controls. Here, however, only a general discussion of each of these mechanisms is presented to show the complexity of the problem.

Global climate change is often considered to be the best candidate for having controlled the changes of terrestrial biotas and the decline of peat-forming habitats at a Euramerican scale. The onset of greenhouse conditions, the first indication of which appeared at the end of the Westphalian, is ascribed either to extra-terrestrial influence or to long-lasting geological processes related possibly to large geotectonic cycles of amalgamation and breaking up the continents. Increased activity of rifting-processes resulting in a disintegration of continents could produce large amount of CO₂ due to strong volcanism, and its increase in the atmosphere could have produced a greenhouse effect. The impact of such a climate change would be expected to be global and more or less isochronous. Climate change could be gradual or cyclic, characterised by alternations of drier and wetter periods, with each drier interval becoming more severe than the previous ones, whereas the wetter intervals would tend to be gradually shorter and less prominent. This second scenario is supported by the sedimentary record in the Stephanian, which is characterized by alternating intervals of coal-bearing strata and red-beds. This alternation has been observed in most of the Euramerican coal basins, and might be related to the

interference of two or even more independent climatic trends of various periodicities. Attempts to correlate these basin-wide 'grey' and 'red' beds indicate a basic agreement in their stratigraphical position within most of this area. The first drier period spans the interval of the lower Stephanian (approximately Barruelian). The second most prominent drier period is of late Stephanian age, from which it grades further into the Autunian. Both periods are separated by wetter period of middle Stephanian (Stephanian B) age, with economically important coal seams occurring in many basins where sediments of this age are developed. Exceptions might be related either to discrepancies in the determination of precise stratigraphical position of lithostratigraphical units in particular basins, or to its overprint by other mechanisms, especially by local climate or tectonics. One of the main objections against the climatically controlled floristic change is the persistence of lycophyte-dominated coal measure forests in China (Liu, 1990) until the end of the Permian. However, this may be explained by the relatively isolated palaeogeographical position of China remote from the main Pangaea landmass. Thus, China was surrounded mostly by ocean and so could be exposed to a wetter climate, despite the drying trend in Euramerica.

Tectonic processes related to the Variscan Orogeny and Pangaea assembly are another possible control responsible for the floristic changes and the decline in the peat-forming habitats. Tectonic processes could produce local as well as regional changes in rate of subsidence and consequently in base-level. Consequently, it could be responsible for wetter table fluctuation and quality of drainage, and also for mire development. Deceleration of base level rise can result in improved drainage and consequently water-table drop, which could in turn result in the decline in the mires. A similar effect was described in eustatically-driven cyclothems, in which mire formation is related to a certain rate of base-level rise (Falcon-Lang, 2003).

Tectonically induced base-level changes are also responsible for breaks in deposition and erosion of older strata, if the base-level is falling down. These processes might be local or regional, with a more or less regular to strongly irregular pattern of base-level changes.

The influence of tectonics is the most prominent in continental and foreland basins, where this mechanism is the main producer of basin subsidence. In the North Variscan Foredeep, continuing compression resulted not only in a northward migration of the depocentre, but finally in an onset of basin-inversion and interruption/termination of deposition at the beginning of the Stephanian and is considered to be one of the most important controls on deposition in continental basins.

The persistence of coal measure forests in China is easily explained by the palaeogeographical position of the North and South China blocks, which are distant from the influence of these Variscan orogenic processes.

Rising of orographic barriers produced by collisional processes is another widely discussed mechanism (Cecil et al., 1985; Rowley et al., 1985; Calder and Gibling, 1994) which could be responsible for local to regional rain-shadows or irregularities in distribution of precipitation. The several thousand metres high altitude proposed for the Variscan Mountains (e.g. Mattauer, 1986; Becq-Giraudon et al., 1996) could produce effects similar to those of the rising of the Himalaya Mountains during the Tertiary. In both cases, the mountain-chain is located between ocean and basins, thus providing an orographic barrier against wet ocean winds. Rising of mountainous relief might be a relatively fast process, lasting 'only' several million years to produce several thousand metres of high topography, but it is quite a long process comparable to the longevity of certain terrestrial biotas. However, one of the most crucial objections against the principal role of topography is that the main control on floristic changes is the culmination of orogenic processes and mountain building during the Viséan, which did not have any prominent effect on the persistence of the Namurian and Westphalian lowland ecosystems in North Variscan foreland and adjacent paralic and intermontane basins. Consequently, rather local differences in microclimate concerning the wetness are considered. These, however, can produce local anomalies which can play an important role when correlating events between individual basins.

The Euramerican coal province was located around the palaeoequator with its western part generally south of the palaeoequator and its eastern part north of the palaeoequator. The northwards drift of Pangaea during the Late Palaeozoic resulted in a gradual shift of the Euramerican coal province through the latitudinal climate belts by the Late Permian. This migration to latitudes of drier climate might be really responsible for the long-lasting general trend of an increase in dry conditions, observed since the end of the Westphalian through the Stephanian to the Permian, whereas superimposed periodic alternation of wetter and drier pulses could possibly be ascribed to orbitally-driven cycles.

To recognize how the above mentioned controls are responsible for changes in terrestrial biotas, as well as the intensity of their effect, requires careful correlation of palynological, macrofloristic and sedimentological data from the various basins of the Euramerican coal province. Com-

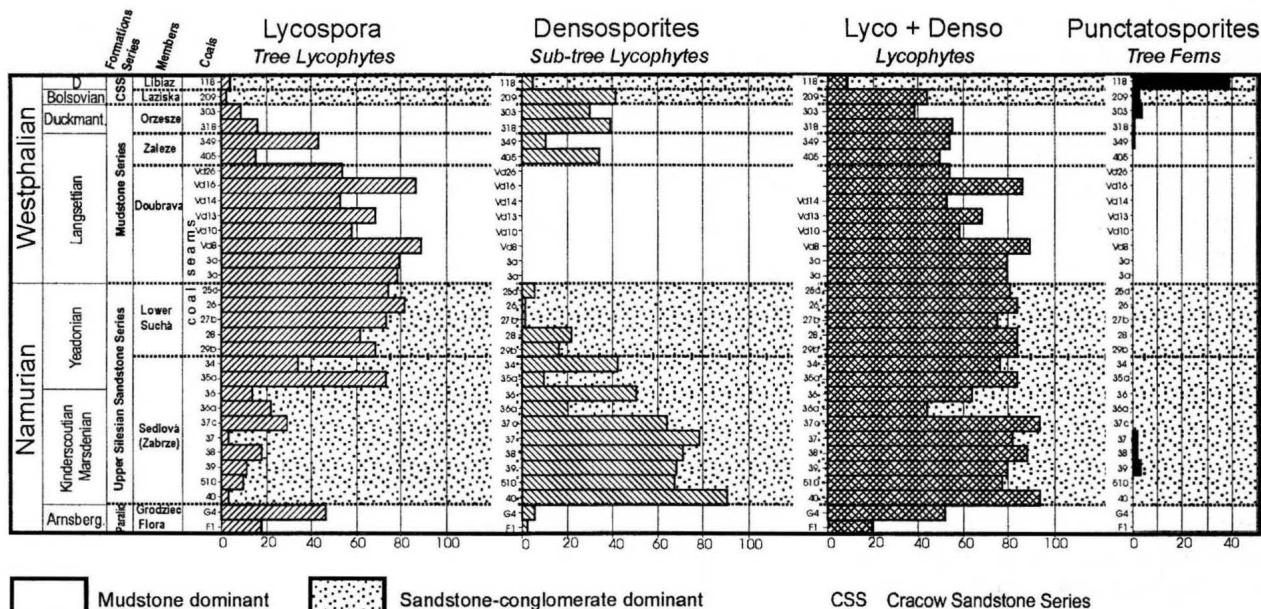


Fig. 5. Changes in miospore abundances of selected plant-groups in the coal seams of the Upper Silesian Coal Basin showing the declining of lycosids towards the end of the Westphalian. Prepared from data published by Dybová-Jachowiczova and Jachowicz (1975) and unpublished data of Valterová (1977, 1978, 1980, 1983)

parison of basins of various palaeogeographical and geotectonic positions can revealed the most important controls in each basins and to postulate which are local and which are global in effect, and how they controlled the changes in terrestrial biotas, especially in the tropical lowland ecosystems.

Coal-bearing, or at least fossiliferous, strata recording the Westphalian – Stephanian transition are preserved only in certain basins of the Euramerican coal province. In North America, this interval is preserved in all the most important basins, including the Western and Eastern Interior Basins, the Appalachian Basin, and in the Sydney Coalfield of the Canadian Maritimes Basin. These basins, located in the eastern half of the North American continent, occupy different geotectonic and palaeogeographical positions. The Interior basins, located in the western part of the American Craton, are characterised by slow thermal subsidence with only weak tectonic activity from distant orogenes. Coal seams are present even in the lower and middle Stephanian, but are less frequent and economically important in comparison to those in the upper Westphalian strata. Due to the absence of any strong tectonic influence, the Interior basins provide excellent conditions for the examination of the effects of climatic and palaeogeographical influences on changes of terrestrial biotas. The Appalachian Basin is a typical foreland basin, affected by compressional tectonic processes from the adjacent Appalachian Orogen producing depocenter-migration, difference in subsidence, and folding of part of the basin fill. It

also provides coal-bearing Stephanian strata, despite the apparent decrease in frequency of coal seams at the base of the Stephanian. The Interior and Appalachian Basins contain marine bands up to the lower Stephanian, in contrast to western and central Europe where the last marine incursions took place during the Bolsovian. Their presence could be very helpful when correlating the floristic changes across this continent. The Maritimes Basin in Atlantic Canada provides a coal-bearing transition through the Westphalian D into the Cantabrian in a setting of thermal subsidence. As a whole, the North American coal basins provide excellent conditions for the study of floristic changes around the Westphalian – Stephanian boundary in different palaeogeographical and tectonic settings, thus allowing the examination of the various mechanisms discussed above.

In Europe, the Westphalian – Stephanian transition is preserved generally in smaller, tectonically controlled basins or coalfields, scattered over a large area in different palaeogeographical positions, ranging from foreland to orogene interior. An uninterrupted transition in coal-bearing or fossiliferous development occurs in the South Wales and Dobrudzha Coalfields, located at opposite ends of the European Variscides. It is also developed in basins of central and western Bohemia, in the Intra Sudetic Basin, and possibly also in the Upper Silesian Coal Basin (Fig. 5). Unfortunately, there is a hiatus at this stratigraphical level in the Saar-Lorraine. Only minor breaks are also reported from the basins in the South Carpathians

in Romania. In the Erzgebirge Basin, only Westphalian D strata occur. Similarly, in most coalfields of the North Variscan Foreland, only Westphalian D strata occur at the top of the Pennsylvanian coal-bearing succession. However, comparison of the South Wales and Dobrudzha Coalfields, with continental basins of the Variscan interior, could provide interesting results concerning especially the interference of tectonic and climatic influences on terrestrial biotas. However, relative abundance of endemics in the continental basins may serve as an obstacle when correlating the stratigraphies of these basins with those of the North Variscan Foreland.

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References

- Becq-Giraudon J.F., Montenat, Ch., Van Den Driessche, J. 1996. Hercynian high-altitude phenomena in the French Massif Central: the tectonic implications. – *Palaeogeog., Palaeoclim., Palaeoecol.*, 122: 227-241.
- Bek, J., Opluštil, S. 2004. (in press). Palaeoecological constraints of some *Lepidostrobus* cones and their parent plants from the Late Paleozoic continental basins of the Czech Republic. – *Rev. Palaeobot. Palynol.*
- Besly, B.M. 1988. Palaeogeographic implications of late Westphalian through early Permian red-beds, central England. – In: Besly, B.M., Kelling, G. (eds) *Sedimentation in a synorogenic basin complex. The Upper Carboniferous of NW Europe*. Blackie, Glasgow, pp. 200-221.
- Besly, B.M., Cleal, C.J. 1997. Upper Carboniferous stratigraphy of the West Midlands (UK) revised in the light of borehole geophysical logs and detrital compositional suites. *Geol. J.*, 32: 85-118.
- Blake, B.M., Cross, A.T., Eble, C.F., Gillespie, W.H., Pfefferkorn, H.W. 2002. Selected plant megafossils from the Carboniferous of the Appalachian region, Eastern United States: Geographic and Stratigraphic Distribution. – In: Hills, L.V., Henderson, C.M., Bamber, E.W. (eds) *Carboniferous and Permian of the World*. – *Can. Soc. Petrol. Geol. Mem.*, 19: 259-335.
- Calder, J.H. 1979. Effect of subsidence and depositional environment on the formation of lithotypes in a hypautochthonous coal of the Pictou Coalfield. – *Nova Scotia Dept. Mines, Paper*, 79-6; 1-23.
- Calder, J.H. 1998. The Carboniferous evolution of Nova Scotia. – In: Blundell, D., Scott, A.C. (eds) *Lyell: The past is the key to the present*. Geological Society, London (Special Publication), pp. 296-331.
- Calder, J.H., Gibling, M.R. 1994. The Euramerican Coal Province: controls on Late Palaeozoic peat accumulation. – *Palaeogeog., Palaeoclim., Palaeoecol.*, 106: 1-21.
- Cecil, C.B. 1990. Paleoclimatic controls on stratigraphic repetition of chemical and clastic rocks. – *Geology*, 18: 553-536.
- Cecil, C.B., Stanton, R.W., Neuzil, S.G., Dulong, F.T., Rupert, L.F., Pierce, B.S. 1985. Paleoclimate controls on Late Palaeozoic sedimentation and peat formation in the Central Appalachian Basin (U.S.A.). – *Int. J. Coal Geol.*, 5: 195-230.
- Cleal, C.J. 1984. The recognition of the base of the Westphalian D Stage in Britain. – *Geol. Mag.*, 121: 125-129.
- Cleal, C.J. 1991. Carboniferous and Permian biostratigraphy. – In: Cleal, C.J. (ed.) *Plant fossils in geological investigation: the Palaeozoic*. Ellis Horwood, Chichester, pp. 182-215.
- Crowell, J.C. 1978. Gondwanan glaciation, cyclothems, continental positioning, and climate change. – *Am. J. Sci.*, 278: 1345-1372.
- Daber, R. 1955. Pflanzengeographische Besonderheiten der Karbonflora des Zwickau-Lugauer Steinkohlenreviers. – *Beih. Zeit. Geol.*, 13: 1-95.
- Davies, S.J., Gibling, M.R. 2003. Architecture of coastal and alluvial deposits in an extensional basin: the Carboniferous Joggins Formation of eastern Canada. – *Sedimentology*, 50: 415-439.
- DiMichele, W.A., Pfefferkorn, H.W., Phillips, T.L. 1996. Persistence of Late Carboniferous tropical vegetation during glacially driven climatic and sea-level fluctuations. – *Palaeogeog., Palaeoclim., Palaeoecol.*, 125: 125-128.
- DiMichele, W. A., Phillips, T. L. 1994. Paleobotanical and paleoecological constraints on models of peat formation in the Late Carboniferous of Euramerica. – *Palaeogeog., Palaeoclim., Palaeoecol.*, 106: 39-90.
- Doktor, M. 2003. Development of phytogenic deposits in a meandering fluvial system (Mudstone Series, Pennsylvanian (Upper Carboniferous), South Poland). – In: *Volumes of Abstracts, International Congress on Carboniferous and Permian Stratigraphy*. Utrecht, p. 125.
- Dragastan, O., Popa, M., Ciupercianu, M. 1997. The Late Palaeozoic phytostратigraphy and paleoecology of the Southern Carpathians (Romania). – *Acta Palaeont. Romaniaae*, 1: 57-64.
- Dreesen, R. Bossiroy, D., Duser, M., Flores, R.M., Verkaeren, P. 1995. Overview of the influence of syn-sedimentary tectonics and palaeo-fluvial systems on coal seam and sand body characteristics in the Westphalian C strata, Campine Basin, Belgium. – In: Whateley, M.K.G., Spears D.A. (eds) *European Coal Geology*. Geological Society, London (Special Publication No. 82), pp. 215-232.
- Drumond, C.N., Wilkinson, B.H. 1993. Carbonate cycle stacking patterns and hierarchies of orbitally forced eustatic sealevel change. – *J. Sediment. Petrol.*, 63: 369-377.
- Eble, C.F., Greb, S.F., Williams, D.A. 2001. The geology and palynology of Lower and Middle Pennsylvanian strata in the Western Kentucky Coal Field. – *Int. J. Coal Geol.*, 47: 189-206.
- England, P., Houseman, G. 1989. Extension during continental convergence, with application to the Tibetan Plateau. – *J. Geophys. Res.*, 94, 17: 561-579.
- Falcon-Lang, H.J. 1999. Fire ecology of a Late Carboniferous floodplain, Joggins, Nova Scotia. – *Jl Geol. Soc. Lond.*, 156: 137-148.
- Falcon-Lang, H.J. 2003. Response of Late Carboniferous tropical vegetation to transgressive-regressive rhythms at Joggins, Nova Scotia. – *Jl Geol. Soc. Lond.*, 160: 643-648.
- Frakes, L.E., Francis, J.E., Syktus, J.I. 1992. *Climate modes of the Phanerozoic*. Cambridge Univ. Press, Cambridge.
- Franke, D. 1990. Der präpermische Untergrund der Mitteleuropäischen Senke – Fakten und Hypothesen. – *Niedersächs. Akad. Geowiss. Veröff.*, 4: 19-75.
- Gibling, M.R., Calder, J.H., Ryan, R.J., Van de Poll, H.W., Yeo, G.M. 1992. Late Carboniferous and Early Permian drainage patterns in Atlantic Canada. – *Can. J. Earth Sci.*, 29: 338-352.
- Gastaldo, R.A. 1977. A Middle Pennsylvanian nodule flora from Carterville, Illinois. – In: Romans, R.C. (ed) *Geobotany*. Plenum, New York, pp. 133-155.
- Gastaldo, R.A., DiMichele, W.A., Pfefferkorn, H.W. 1996.

- Out of the Icehouse into the Greenhouse: A Late Paleozoic analog for modern global vegetation change. – *GSA Today*, 6; 1-7.
- Gradzinski, R., Doktor, M., Slomka, T. 1995. Depositional environments of the coal-bearing Cracow Sandstone Series (Upper Westphalian), Upper Silesia, Poland. – In: Gradzinski, R., Porebski, S.J. (eds) Carboniferous Upper Silesia Coal Basin: case studies in sedimentology and basin evolution. – *Stud. Geol. Polon.*, 108; 149-170.
- Guion, P.D., Fulton, I.M., Jones, N.S. 1995. Sedimentary facies of the coal-bearing Westphalian A and B north of the Wales-Brabant High. – In: Whateley, M.K., Spears, D.A. (eds) *European Coal Geology*. Geological Society, London (Special Publication, 82); pp. 45-78.
- Hacquebard, P.A., Barss, M.S., Donaldson, J.R. 1960. Distribution and stratigraphic significance of small spore genera in Upper Carboniferous of the Maritime Provinces of Canada. – *C. r. 4e Congr. Int. Strat. Géol. Carbon.*, 1; 237-245.
- Hampson, G.J. 1995. Discrimination of regionally-extensive coals in the Upper carboniferous of the Pennine Basin, U.K. using high-resolution sequence stratigraphic concepts. – In: Whateley, M.K., Spears, D.A. (eds) *European Coal Geology*. Geological Society, London (Special Publication, 82); pp. 79-97.
- Heckel, P.H. 1986. Sea-level curve for Pennsylvanian eustatic marine transgressive-regressive depositional cycles along midcontinent outcrop belt, North America. – *Geology*, 14; 330-334.
- Heckel, P.H. 1994. Evaluation of evidence for glacio-eustatic control over marine Pennsylvanian cyclothems in North America and consideration of possible tectonic effects. – In: Dennison, J.M., Ettenson, F.R. (eds) Tectonic and eustatic controls on sedimentary cycles. – *SEPM Concepts Sediment. Paleont.*, 4; 65-87.
- Heckel, P.H. 1995. Glacial-eustatic base-level-climatic model for late Middle to Late Pennsylvanian coal-bed formation in the Appalachian Basin. – *J. Sed. Res.*, B65; 348-356.
- Heckel, P.H. 2002. Overview of Pennsylvanian cyclothems in Midcontinent North America and brief summary of those elsewhere in the world. – In: Hills, L.V., Henderson, C.M., Bamber, E.W. (eds) Carboniferous and Permian of the World. – *Can. Soc. Petrol. Geol., Mem.*, 19; 79-98.
- Klein, G. de V. 1990. Pennsylvanian time scales and cycle periods. – *Geology*, 18; 455-457.
- Kosanke, R.M., Cecil, C.B. 1996. Late Pennsylvanian climate change and palynomorph extinctions. – *Rev. Palaeobot. Palynol.*, 90; 113-140.
- Kotas, A. 1995. Lithostratigraphy and sedimentologic-paleogeographic development – Upper Silesian Coal Basin. – In: Zdanowski, A., Żakowa, H. (eds) The Carboniferous System in Poland. – *Prac. Panstw. Inst. Geol.*, 68; 124-134.
- Mattauer, M. 1986. Intracontinental subduction, crust mantle décollement and crustal stacking wedge in the Himalaya and others collision belts. – In: Coward, M.P., Ries, A.C. (eds) *Collision tectonics*. Geological Society, London (Special Publication, 19); pp. 115-157.
- Nelson, W.J., Trask, C.B., Jacobson, R.J., Damberger, H.H., Williamson, A.D., Williams, D.A. 1991. Absaroka Sequence, Pennsylvanian and Permian Systems. – In: Leighton, M.W. et al. (eds) Interior cratonic basins. – *AAPG Mem.*, 51; 143-164.
- Laveine, J.P. 1977. Report on the Westphalian D. – In: Holub, V., Wagner, R.H. (eds) *Symposium on Carboniferous Stratigraphy*. Ústø. úst. geol., Prague; pp. 71-87.
- Liu, G. 1990. Permo-Carboniferous paleogeography and coal accumulation and their tectonic control in the North and South China continental plates. – *Int. J. Coal Geol.*, 16; 73-117.
- Mahaffy, J.F. 1988. Vegetation history of the Springfield coal (Middle Pennsylvanian of Illinois) and the distribution of the tree fern miospore *Thymospora pseudothiessenii*, based on miospore profiles. – *Int. J. Coal Geol.*, 10; 239-260.
- Matte, P. 2001. The Variscan collage and orogeny (480-290 Ma) and the tectonic definition of the Armorica microplate: a review. – *Terra Nova*, 13, 2; 122-128.
- Pašek, J., Urban, M. 1990. The tectonic evolution of the Plzeň basin (Upper Carboniferous, West Bohemia): a review and reinterpretation. – *Folia Mus. Rer. natur. Bohem. occident., Geol.*, 32.
- Peppers, R.A. 1985. Comparisson of miospore assemblages in the Pennsylvanian System of the Illinois Basin with those in the Upper Carboniferous of Western Europe. – *C. r. 9e Congr. Int. Strat. Géol. Carbon.*, 2; 483-502.
- Peppers, R.A. 1996. Palynological Correlation of Major Pennsylvanian (Middle and Upper Carboniferous) Chronostratigraphic Boundaries in the Illinois and other Basins. – *Geol. Soc. Amer. Mem.*, 188; 1-111.
- Peppers, R.A. 1997. Palynology of the Lost Branch Formation of Kansas – new insights on the major floral transition at the Middle-Upper Pennsylvanian boundary. – *Rev. Palaeobot. Palynol.*, 98; 223-246.
- Pešek, J. 1994. *Carboniferous of Central and Western Bohemia (Czech Republic)*. Czech Geol. Survey, Prague.
- Pešek, J., Opluštil, S., Kumpera, O., Holub, V., Skošek, V. 1998. *Paleogeographic Atlas, Late Paleozoic and Triassic Formations, Czech Republic*. Czech Geological Survey, Prague.
- Pešek, J., et al. 2001. *Geologie a ložiska svrchnopaleozoických limnických pánví České republiky*. Czech Geological Survey, Prague.
- Pietzsch, K. 1956. *Abriß der Geologie von Sachsen*. Deutsche Verlag der Wissenschaften.
- Pfefferkorn, H.W. 1979. High diversity and stratigraphic age of the Mazon Creek Flora. – In: Nitecki, M.H. (ed.) *Mazon Creek fossils*. Academic Press, New York; pp. 129-142.
- Pfefferkorn, H.W., Gastaldo, R.A., DiMichele, W.A. 2000. Ecological stability during the Late Paleozoic cold interval. – In: Gastaldo, R.A., DiMichele, W.A. (eds) Phanerozoic Terrestrial Ecosystems. – *Paleont. Soc. Spec. Pap.*, 6; 63-78.
- Pfefferkorn, H.W., Mustafa, H., Hass, H. 1975. Quantitative Charakterisierung oberkarboner Abdruckfloren. – *Neues Jahrb. Geol. Palaeontol. Abh.*, 150; 253-269.
- Phillips, T.L., Peppers, R.A., DiMichele, W.A. 1985. Stratigraphic and interregional changes in Pennsylvanian coal swamp vegetation: environmental inferences. – *Int. J. Coal Geol.*, 5; 43-109.
- Plint, A.G., van de Poll, H.W. 1984. Structural and sedimentary history of the Quaco Head area southern New Brunswick. – *Can. J. Earth Sci.*, 21; 753-761.
- Rowley, D.B., Raymond, A., Parrish, J.T., Lottes, A.L., Scotese, C.R., Ziegler, A.M. 1985. Carboniferous paleogeographic, phytogeographic, and paleoclimatic reconstructions. – *Int. J. Coal Geol.*, 5; 7-42.
- Scotese, C.R., McKerrow, W.S. 1990. Revised world map and introduction. – In: McKerrow, W.S., Scotese, C.R. (eds) Palaeozoic palaeogeography and biogeography. – *Geol. Soc. Lond. Mem.*, 12; 1-21.
- Smith, A.H.V., Butterworth, M.A. 1967. Miospores in coal seams of the Carboniferous of Great Britain. – *Spec. Pap. Palaeontol.*, 1; 1-324.
- Šetlík, J. 1970. *Fytopaleontology of the Lower Red Formation*. Unpublished report, Archive of the Czech Geological Survey, Prague [In Czech].
- Šetlík, J. 1977. Results on recent investigation on the Carboniferous flora of Bohemia. – In: Holub, V., Wagner, R.H.

- (eds) *Symposium on Carboniferous Stratigraphy*. Ústř. úst. geol., Prague; pp. 315-340.
- Tenchov, Y. 1989. Possible position of the Variscan chains between the Balkan and Caucasus. – *Geol. Balcanica*, 19, 3; 3-7.
- Tenchov, Y. 1993. Sedimentation and erosion during the Late Carboniferous in the Dobrudzha Coal Field (North-East Bulgaria). – *Geol. Balcanica*, 23, 2; 3-18.
- Turner, N. 1994. *Westphalian D aged palynomorphs from the Halesowen Formation at Cliff Quarry, near Dost Hill, Tamworth*. British Geological Survey, Keyworth (Tech. Rpt WH/94/73R).
- Veevers, J.J., Powell, C.McA. 1987. Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive-regressive depositional sequences in Euramerica. – *Bull. Geol. Soc. Am.*, 98; 475-487.
- Wagner, R.H. 1977. Comments on the Upper Westphalian and Stephanian floras of Czechoslovakia, with particular reference to their stratigraphic age. – In: Holub, V., Wagner, R.H. (eds) *Symposium on Carboniferous Stratigraphy*. Ústř. úst. geol., Prague; pp. 441-457.
- Wagner, R.H. 1993. Climatic significance of the major chronostratigraphic units of the Upper Palaeozoic. – *C. r. 12e Congr. Int. Strat. Géol. Carbon.*, 1; 83-108.
- Wagner, R.H., Lyons, P.C. 1997. A critical analysis of the higher Pennsylvanian megafloras of the Appalachian region. – *Rev. Palaeobot. Palynol.*, 95; 255-283.
- Wanless, H.R., Shepard, F.P. 1936. Sea level and climatic changes related to late Palaeozoic cycles. – *Geol. Soc. Am. Bull.*, 47; 1177-1206.
- Wanless, H.R., Weller, J.M. 1932. Correlation and extent of Pennsylvanian cyclothems. – *Geol. Soc. Am. Bull.*, 43; 1003-1016.
- Weithofer, K.A. 1896. Die geologischen Verhältnisse des Bayer-Schachtes und benachbarten Teiles der Pilsner Kohlenmulde. – *Österr. Z. Berg- u. Hüttenwes.*, 44; 317-321, 331-335, 345-349, 355-357.
- Weithofer, K.A. 1902. Geologische Skizze des Kladno – Rakonitzer Kohlenbeckens. – *Verh. K.-Kön. geol. Reichsanst.*, 399-420.
- White, J.C., Gibling, M.R., Kalkreuth, W.D. 1994. The Backpit seam, Sydney Mines Formation, Nova Scotia: A record of peat accumulation and drowning in a Westphalian coastal mire. – *Palaeogeog., Palaeoclim., Palaeoecol.*, 106; 223-239.
- Ziegler, P.A. 1990. *Geological Atlas of western and central Europe*. Shell, The Hague.