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Significant hiatuses in the terrestrial Late Variscan Central and Western Bohemian basins (Late Pennsylvanian–Early Cisuralian) and their possible tectonic and climatic links

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Abstract: Significant changes in the stratigraphy of the Central and Western Bohemian Upper Palaeozoic basins occur during or shortly after hiatuses. The different extent and changes in the depocentres of the Radnice and Nýřany members (Moscovian) in the Plzeň Basin clearly indicate changes in the structure of this basin taking place during a break in sedimentation between these two units (311.9–308.3 Ma). Thick weathered rocks that occur in boreholes in the Mšeno–Roudnice Basin indicate another sedimentation break (305.9–304.1 Ma) between the Nýřany Member and the Týnec Formation (Kasimovian). Another possible hitherto undiscovered hiatus occurred between the Týnec and Slaný formations (Kasimovian–Gzhelian, about 304–303 Ma). The most significant changes in the configuration of the basins occurred between the Slaný and Líně formations (Gzhelian–Asselian, 301.6–300.6 Ma). This is indicated by deeply cut river valleys at the top of the Slaný Formation, by high thickness of weathered deposits occurring immediately beneath the Líně Formation, and mainly by the shift of depocentres from the southern to the northern part of the Central Bohemian basins. The hiatuses between the Radnice and Nýřany members and between the Slaný and Líně formations are accompanied by significant changes in the depocentres, and they are therefore interpreted primarily as tectonic events related to the extensional collapse of the Variscan orogenic belt. By contrast, the hiatuses beneath and above the Týnec Formation are interpreted as being the products of lower sedimentation rates during drier climates, which is consistent with the characteristics of the sediments, correlation with other Central European basins, and with climate models for this period. Due to the characteristics of the Líně Formation, in which the effects of climate aridization are clearly seen, the authors presume that tectonic as well as climatic changes occurred at the hiatus between the Slaný and Líně formations.

Keywords: Pennsylvanian, Cisuralian, terrestrial basins, hiatuses, climate changes, tectonics, weathering.

Introduction

The Bohemian Massif is the easternmost and also the largest block of the eastern branch of the Variscides. This area was formed during the Carboniferous as a result of the collision of Baltica (the eastern branch of Laurasia) and Gondwana, when, during simultaneous rotation, the new supercontinent Pangea was formed (Kearey et al. 2009). Variscan processes of considerable intensity occurred in the territory of present-day Central Europe because of its location in the collision zone. The emerging Variscan orogeny also incorporated older, particularly Cadomian consolidated blocks such as the Vosges, the Black Forest and the Bohemian Massif (Kroner et al. 2008). The regressive nature of Middle Devonian sediments and subsequent termination of sedimentation in the Prague Basin reflect the onset of the Variscan Orogeny, which culminated in the Bohemian Massif in the Late Visean. At that time, folding of Cambrian to Early Namurian (Serpukhovian) sediments occurred in this area (McCann et al. 2008). The youngest deposits that were folded in the Bohemian Massif are the sediments, tuffs and tuffites of the Ostrava Formation in the Czech part of the Upper Silesian Basin (folded as early as between the Lower and Middle Namurian, comp. Dopita et al. 1997), which is a foreland basin partially filled with paralic deposits. The other Late Palaeozoic basins in the Czech Republic are terrestrial intermontane basins, which formed primarily in an extensional or transtensional regime.

Arthaud & Matte (1977) deduced that these types of basins formed as a result of the extensional collapse of the Variscan orogenic belt after the collision of Gondwana and Baltica, which reactivated older NW–SE oriented fault structures transforming them into normal faults and predominantly right-lateral strike-slip faults. According to Ziegler (1990), the formation of the Late Palaeozoic terrestrial basins of the Bohemian Massif are probably also related to the movements along these structures and their conjugate equivalents. The fill of these basins never underwent significant folding. Initially, the thickness of deposits was usually more or less influenced by the unevenness of the basin basement. Later, interruptions in sedimentation of variable duration may have occurred in response to the Variscan post-orogenic tectonics and climatic changes.

The terrestrial basins of the Czech Republic include the Western Bohemian, Central Bohemian, Sudetic (Lusatian) and Brandov basins, Blanice and Boskovice grabens, and Late Palaeozoic relics preserved in the surroundings of nearly all basins (Fig. 1). The Western Bohemian basins include the Plzeň Basin, Manětín and Žihle basins and the small Radnice Basin (see Fig. 2). The first three basins, now more or less independent, were undoubtedly connected at least from the Asturian (Moscovian), and a connection to the Radnice Basin cannot be ruled out (Pešek et al. 1998). The Central Bohemian basins include the Kladno–Rakovník and Mšeno–Roudnice basins, which pass into one another. In the west, the fill of the Kladno–Rakovník Basin is separated only formally from the Žihle Basin, whereas in the east, the fill of the Mšeno–Roudnice Basin passes into the Mnichovo Hradiště Basin in the Sudetic (Lusatian) region. Individual basins are thus delimited and named merely historically. The use of the term “basin“ is purely formal and not based on basin structure, as the all basins mentioned above represent a single gradually developing sedimentation basin.

Most of the Central and Western Bohemian basins are filled with the sediments comprising all four formations — the Kladno, Týnec, Slaný and Líně formations of Duckmantian to Autunian age (Moscovian–Asselian) (Table 1). The Kladno and Slaný formations are subdivided into several lithostratigraphic units. The formation of these basins was influenced mainly by two deep-seated faults — the Central Bohemian Fault to the south of the Central and Western Bohemian basins, which has been active since the beginning of Langsettian/Westphalian sedimentation, and, with a slight delay, the gradually increasingly active Litoměřice Fault to the north of all these basins (Havlena & Pešek 1980). The works by Pešek (1994, 2004) provide a detailed description of the lithostratigraphic units, their age and the evolution of the above-mentioned basins. Due to the relatively small area of the Manětín and Žihle basins, and to the lower level of knowledge regarding these basins, this study deals only with the Plzeň Basin and also with the Kladno–Rakovník and Mšeno–Roudnice basins.

Methods and data

The information presented in this paper is based mostly on boreholes drilled from the surface into the basement of the Pennsylvanian after 1945 mainly during the prospecting for and exploration of coal deposits — specifically around 400 boreholes in the Plzeň Basin, about 200 boreholes in the Kladno–Rakovník Basin, and roughly 60 boreholes in the Mšeno–Roudnice Basin. The boreholes in the Plzeň and Kladno–Rakovník basins were drilled primarily by the employees of the former companies Uhelný průzkum (Coal Exploration), later known as Geologický průzkum, n. p. (Geological Exploration, national enterprise) and Geoindustria, n. p.

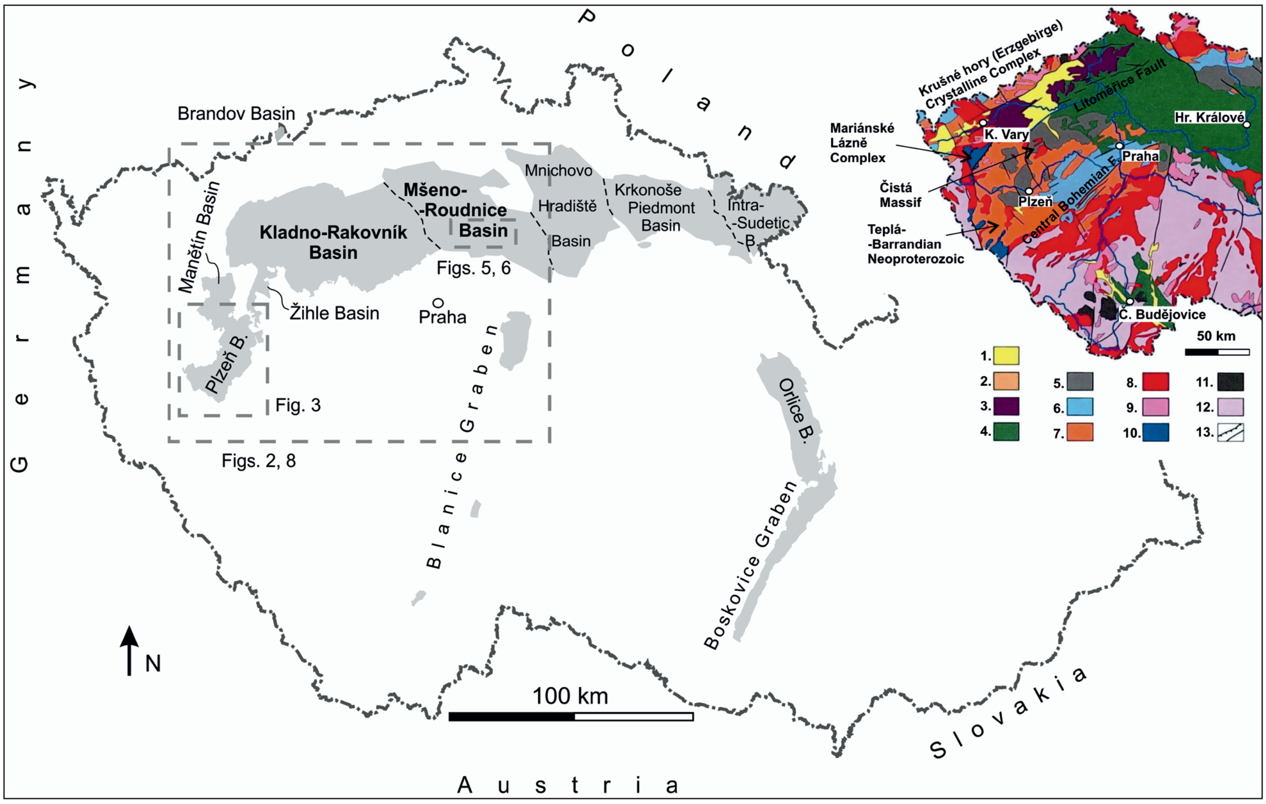

Fig. 1. Upper Palaeozoic continental basins. After Chlupáč & Štorch (1992). Upper right: Simplified geological map of the western part of the Czech Republic without Quaternary cover. Modified after Chlupáč et al. (2002). 1 — Neogene, 2 — Palaeogene, 3 — neovolcanic rocks, 4 — Upper Cretaceous, 5 — Upper Palaeozoic, 6 — Lower Palaeozoic, 7 — Neoproterozoic, 8 — granitoids, 9 — orthogneisses, 10 — different types of basic rocks, 11 — granulites, 12 — Moldanubian Crystalline Complex, 13 — overthrust and normal faults.

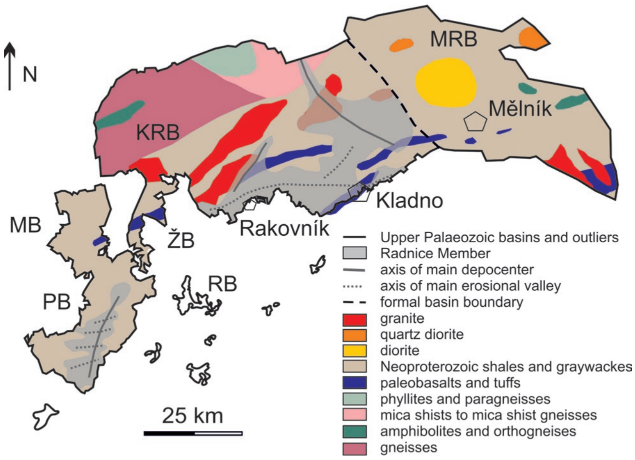

Fig. 2. Relationship of the oldest unit, the Radnice Member, to the geology of the basement. After Pešek (1994). Basins: PB — Plzeň, RB — Radnice, MB — Manětín, ŽB — Žihle, KRB — Kladno–Rakovník, MRB — Mšeno–Roudnice.

The boreholes in the Mšeno–Roudnice Basin, whose fill is completely covered by Upper Cretaceous sediments, were drilled in the 1960s by the former Central Geological Institute (known today as the Czech Geological Survey). These were followed-up in the 1970s and 1980s by the boreholes of Geoindustria, n. p. The second author of this paper, in particular, has had an opportunity to study most of the boreholes as they were being drilled in the Plzeň Basin in the late 1950s and in all of the above-mentioned basins in the 1960s and later.

The boreholes in the Plzeň and Mšeno–Roudnice basins are distributed unevenly but cover a greater part of these basins. This provided detailed information regarding the characteristics and development of the deposits of the Plzeň Basin, primarily in the Radnice and Nýřany members. Due to tectonic development thicker sections of the deposits of the remaining units, namely the Týnec, Slaný and Líně formations, were preserved only in a much smaller area of this basin (see App. II in Pešek 1994). The Radnice Member is absent in the Mšeno–Roudnice Basin except for a small area in the southwest because the deposition of sediments in this basin began mainly in the Nýřany Member. In the Kladno–Rakovník Basin, which began to be filled around the same time as the Plzeň Basin, most of the boreholes were drilled in the southern part of the basin. The Radnice Member occurs only rarely in the remaining part of the Kladno–Rakovník Basin. That is why the data on its thickness and characteristics are sufficient but less detailed when compared with the Plzeň Basin. By contrast, the deposits of the Týnec, Slaný and Líně formations in the Kladno–Rakovník as well as Mšeno–Roudnice basins provide far better evidence regarding the characteristics and significant changes in the evolution of these basins. The data from all the above-mentioned boreholes and even older boreholes were used to compile isopach maps as well as other maps, for example, in the papers of Havlena & Pešek (1980), Pešek (1994) and Pešek et al. (1998).

Hiatuses and their depositional aspects

This study follows the publication of Opluštil et al. (2016) and focuses primarily on the significant changes in sedimentation that occurred during hiatuses in individual basins. It also documents some other possible interruptions in sedimentation, which are more likely of local significance.

Two significant interruptions in sedimentation are thus far known in the Central and Western Bohemian basins: the hiatus between the Radnice and Nýřany members, namely between the Bolsovian and Asturian, as indicated by a macrofloral studies, for example, by Němejc (1937), recently by Opluštil et al. (2016) and the hiatus between the Slaný and Líně formations, namely between Stephanian B and C as reflected, for example, in drill cores by the presence of weathered rocks at the contact of these two units (e.g., Havlena & Pešek 1980; Bosák 1991). It can also be inferred from a significant shift of the depocentres from the southern part of the basin to the north (Pešek 1994). A study of detrital zircons of the volcaniclastic rocks of all the units of the Central and Western Bohemian basins was conducted by Opluštil et al. (2016). In addition to confirming the existence of hiatuses between the above-mentioned units, they identified or verified other thus far mostly unknown or only presumed but not reliably documented hiatuses and their duration (Table 1). These authors revealed a previously unknown hiatuses between the Lower and Upper Radnice members, between the Nýřany Member and

Table 1: Stratigraphic units of the Central and Western Bohemian basins.

Age			Local unit		
Global stage	Regional stage	Substage	Formation	Member	Group of coals
Asselian	Autunian		297.1 Ma Líně 300.6 Ma		Klobuky Zdětín
Gzhelian	Stephanian	C			
		B	hiatus ca 1 Ma		
		Saberian	301.6 Ma Slaný 302.9 Ma	Kounov Ledce Malesice* Jelenice	Kounov Mělník
			hiatus < 1 Ma		
		Barruelian	Týnec 304.1 Ma		
Kasimovian			hiatus ca 1.8 Ma		
	Westphalian	Cantabrian	305.9 Ma Kladno 308.3 Ma	Nýřany	Nevřeň Chotíkov Nýřany Touškov
Moscovian		Asturian			
			hiatus ca 3.6 Ma		
		Bolsovian	311.9 Ma Kladno 314.2 Ma	Radnice	Lubná Radnice Plzeň
		Duckmant.			

* Malesice Member is divided to lower Mšec and upper Hředle members in some places

the Týnec Formation, the existence of which was suggested by Wagner (1977) based on floristic research. In the case of all these hiatuses, Opluštil et al. (2016) were also the first to document the hiatuses duration.

Considerable changes in the evolution of the Central and Western Bohemian basins occurred during a break in sedimentation particularly between the Radnice and Nýřany members (Moscovian) and between the Slaný and Líně formations (Gzhelian). The first of the above-mentioned changes is best demonstrated by the formation of a NW–SE oriented depocentres in the Plzeň Basin (Fig. 3), the second is evident both from a significant change in the configuration of the basins and source areas (e.g., Pešek et al. 1998) and from the changes in dip direction and dip of the mudstones of the Slaný and Líně

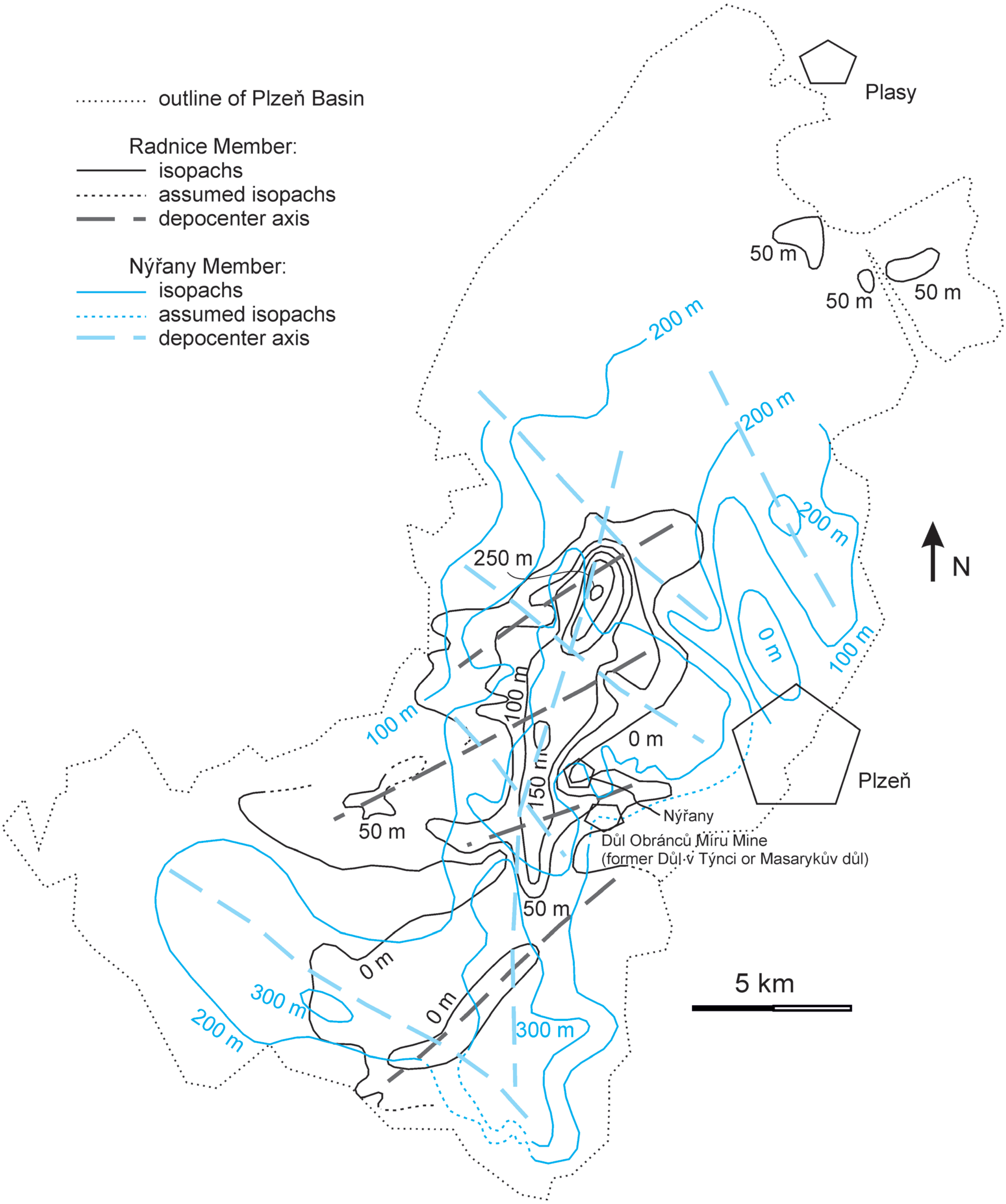

Fig. 3. Isopach maps of the Nýřany and Radnice members in Plzeň Basin. After Pešek (1968).

formations, which were verified by acoustic logging (Svrčinová in Žbánek et al. 1990a, b; Bosák 1991) in the borehole Sč 1 (Semčice) in the Mšeno–Roudnice Basin (Fig. 4a). The acoustic logging was unfortunately not used in other boreholes due to technical reasons, so the authors of this study used the data on the dip of the mudstone beds that were obtained in the boreholes drilled in the Mšeno–Roudnice Basin only (Fig. 4b). The existence of these hiatuses is also indicated by the weathered rocks (i.e primary grey sediment colour is highly altered by motting) at the top of the Nýřany Member and primarily by those of the Slaný Formation (Fig. 5) and also by numerous erosional features in the upper part of the Slaný Formation (Fig. 6) that were previously discovered by Havlena & Pešek (1980) and specified, for example, by Skopec et al. (1990 and 2001). All the data shown in Figures 4a,b and 6 were gathered mainly from boreholes drilled in the 1960s to 1980s in the Mšeno–Roudnice Basin.

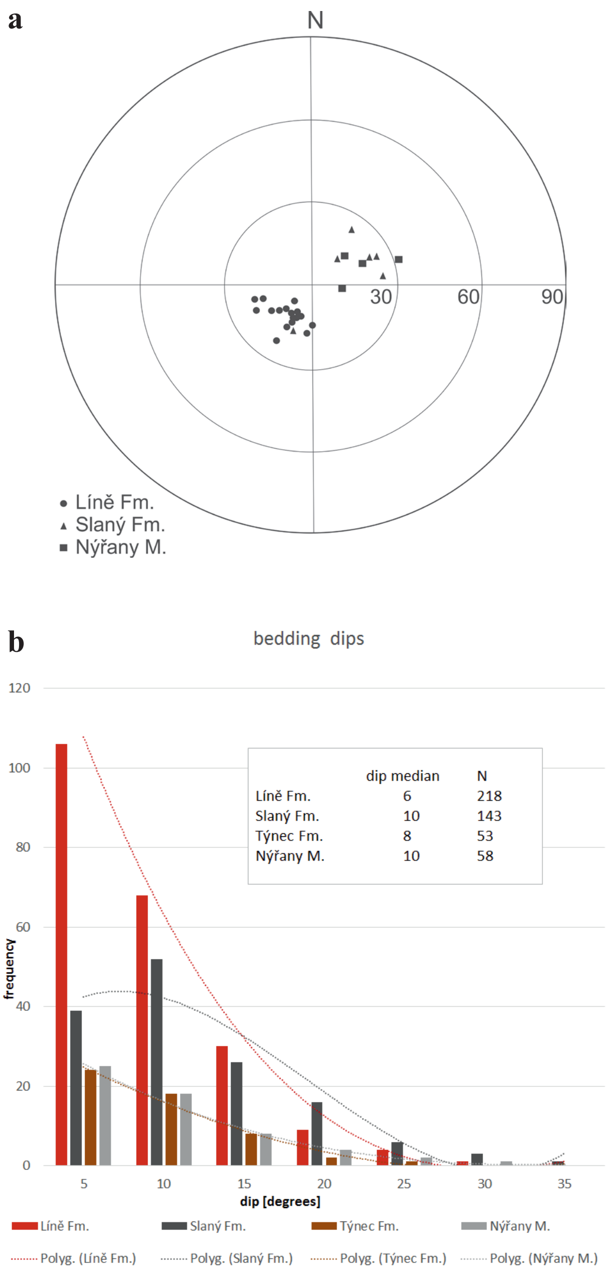

Fig. 4. a — Dip directions and dips of mudstones in the borehole Sš 1 based on acoustic logging. After Svrčinová in Žbánek et al. 1990a. **b** — Bedding dips of mudstones in the Líně, Slaný and Týnec formations and Nýřany Member in drill cores from the Mšeno–Roudnice Basin. Based on numerous unpublished drilling reports.

Relationship between the basement and the basal unit — the Radnice Member

The Radnice Member, of Duckmantian to Bolsovian (Moscovian) age, occurs in the area of the Plzeň, Kladno–Rakovník and Radnice basins (Figs. 1 and 2). It is also known from small occurrences in the Žihle and Mšeno–Roudnice basins and also from a series of small relics that lie in a NE–SW band south of the Central and Western Bohemian basins. The Radnice Member is the most explored unit of this Upper Palaeozoic complex due to a number of boreholes and coal mines that verified its coal–bearing capacity. The influence of the basement on the extent and characteristics of the deposits of this unit can only be studied in the areas of the Plzeň and Kladno–Rakovník basins. Opluštil (2005) made a detailed reconstruction of the river network, of the extent of peatlands and of other specific environments in the Kladno–Rakovník Basin. The lithological characteristics of the deposits of this unit are relatively well-known and also its spatial and temporal changes. It is presumed that the present extent of the Radnice Member is only a relic of the larger area originally covered (see App. 35 in Pešek et al. 1998; Opluštil 2005).

Plzeň Basin

According to Pašek & Urban (1990), the Plzeň Basin is an extensional basin. The so-called central depocentre (Pešek 1968), in which by contrast to its surroundings all four formations were largely preserved, runs approximately through the basin centre in NNE–SSW direction. The central depocentre also predisposes the NNE–SSW elongation of the whole basin. The Radnice Member (Fig. 3) occurs in approximately one half of the basin area (e.g., Dvořák 1960; Havlena & Pešek 1980; Pešek 1994). Folded rocks of the Teplá–Barrandian Neoproterozoic with NE–SW oriented axes occur in the basement of the predominantly volcaniclastic fill of the Plzeň Basin. Bands of variously resistant weakly metamorphosed shales and greywackes alternate with isolated intercalations of palaeobasalts and palaeobasaltic tuffs. Erosion-resistant greywackes and palaeobasaltic rocks form ridges mostly only a few tens of metres high, which protected peatlands evolving in depressions from the input of coarse-grained clastic material. As a result a sediment shadow developed (Pešek 1968), in which several (and rarely up to 14) metres thick seams were formed and mostly grey claystones and siltstones as well as tuffs and tuffites were deposited. The fill of these mainly erosional palaeo-valleys is generally only a few tens of metres

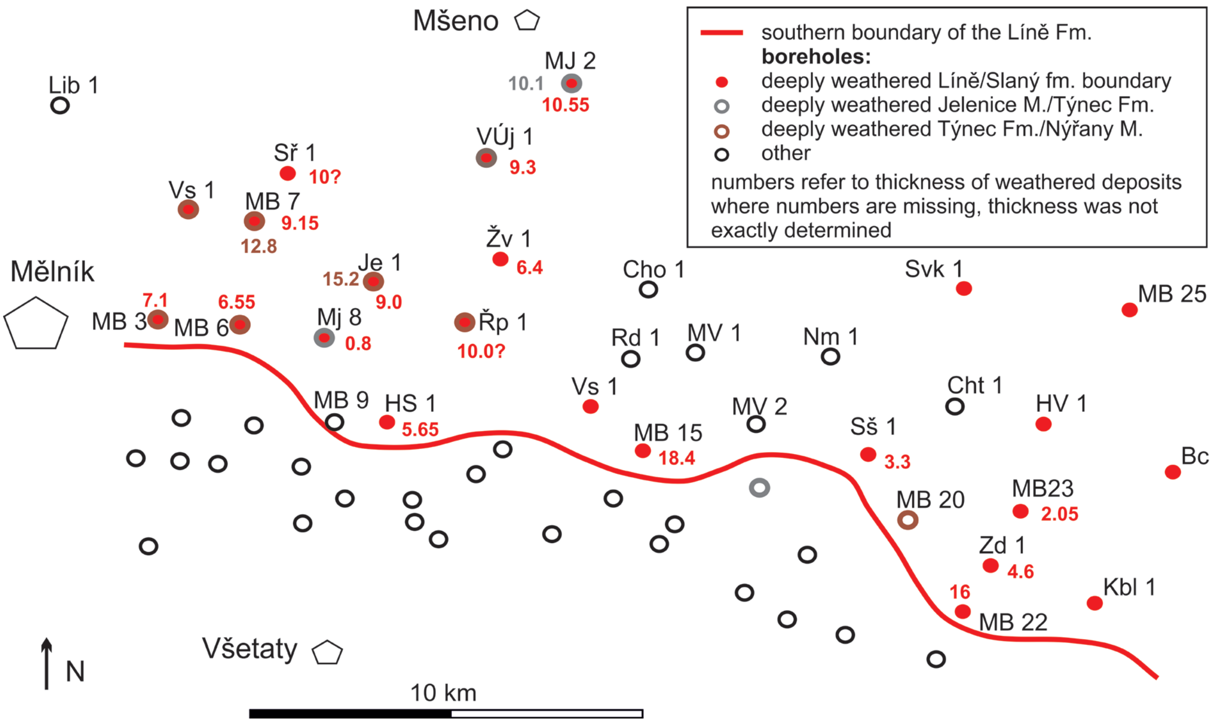

Fig. 5. Deep weathering on the top of the Slaný and Týnec formations and Nýřany Member in the Mšeno–Roudnice Basin. Based on numerous unpublished drilling reports.

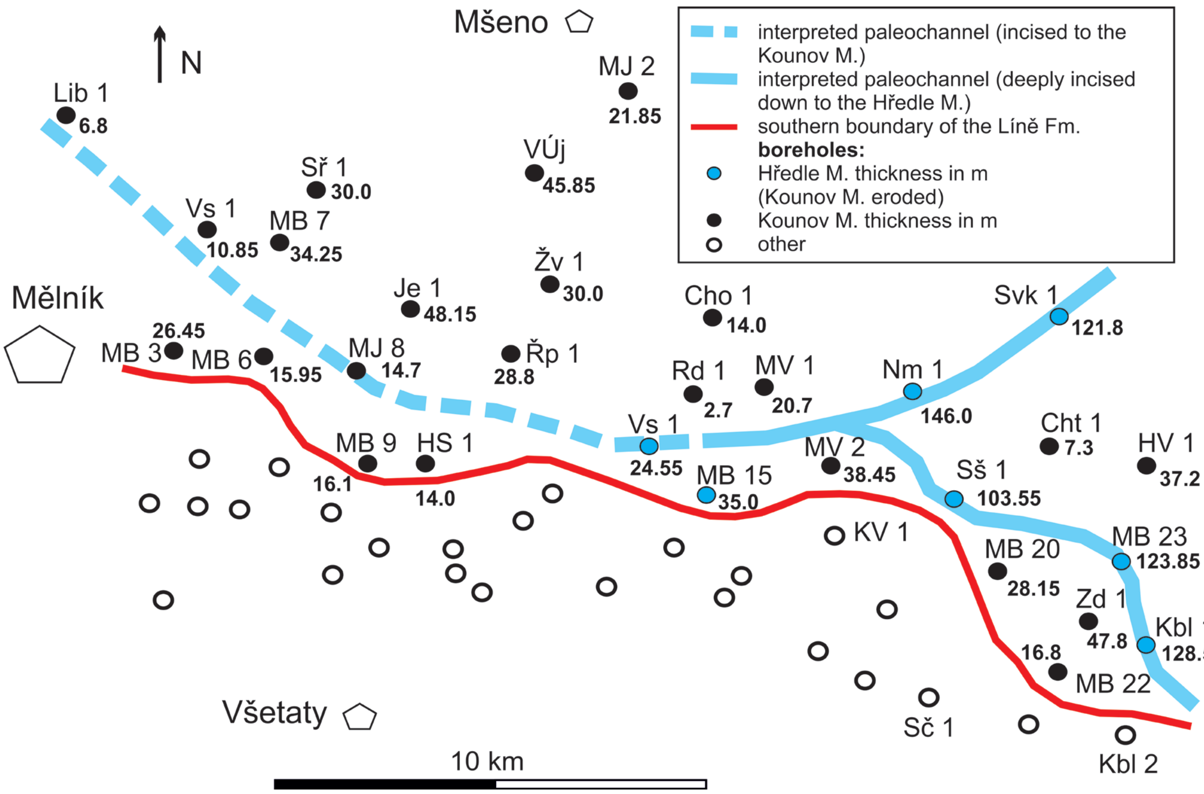

Fig. 6. Erosional features on the top of the Slaný Formation in the Mšeno–Roudnice Basin. Based on numerous unpublished drilling reports.

thick. These depressions are divided into two parts by the NNE–SSW oriented central depocentre. It may have originated either as a deep river valley of unknown age formed by erosion or as a tectonically formed synsedimentary structure. In the Radnice Member, it is filled mainly with up to more than 250 m thick coarse clastic rocks — subarkoses and conglomerates. Coal seams are either entirely absent or only a few tens of centimetres thick.

Kladno–Rakovník Basin

The Kladno–Rakovník Basin is elongated in a roughly ENE direction and tectonically bounded to the north. By contrast, its boundary with the surrounding units to the south and west is mostly erosional. In the east, it passes into the siliciclastic fill of the Mšeno–Roudnice Basin. The Radnice Member fills only about one-third of the area of the Kladno–Rakovník Basin. Even though it is, as in the Plzeň Basin, underlain mostly by folded weakly metamorphosed Neoproterozoic shales and greywackes of the Teplá–Barrandian area, it was verified that it contains several larger bodies of palaeobasalts and palaeobasaltic tuffs as well. The basement also comprises the granites of the Čistá Massif, which continues to the northeast. At the northwest of the basin (Fig. 1), the basement is formed by phyllites, schists and schistose gneisses of the Krušné hory (Erzgebirge) Crystalline Complex. A narrow body of amphibolites of the Mariánské Lázně Complex extends into the basement in the west.

Two significant depocentres were active in the Radnice Member. The first is the Rakovník depocentre in the vicinity of the town of Rakovník, which is narrow and elongated in a NNE direction. It is bounded to the west by the granites of the Čistá Massif (Fig. 1). This is probably the fill of a pre-Late Westphalian river valley that cut not only into the Neoproterozoic shales and greywackes but also into the palaeobasalts and palaeobasaltic tuffs. It comprises a complex of up to more than 260 m thick mostly grey clastic rocks, in which coal seams are either entirely absent or which contain coal seams only a few tens of centimetres thick. Unlike the central depocentre of the Plzeň Basin, this structure was probably not active during the deposition of other lithostratigraphic units. By contrast, the second depocentre, which lies northeast of the Rakovník depocentre and which is elongated in a NW direction and referred to by Havlena & Pešek (1980) as the Zlonice–Peruc depocentre (and by Opluštil 2005 as the Třtěno–Zlonice depocentre), is a structure that is apparently bounded by NW–SE trending faults. In addition to the relatively thick Radnice Member, the more than 500 m thick deposits of the Nýřany Member (see below) were preserved in this structure as well. The extensive, nearly E–W oriented valley, which was filled with coal-bearing deposits, begins near the village of Petrovice west of Rakovník and extends as far as the surroundings of Otvovice near Kladno in the east of this basin (Opluštil 2005). This author rightly presumes the existence of a number of E–W to NW–SE oriented tributary valleys.

Hiatus between the Radnice and Nýřany members

The existence of the hiatus between the Radnice and Nýřany members was already known at the end of the 19th century, as is evident from the palaeobotanical research of Frič (1879) or Purkyně (1899) and from a number of geological and palaeontological papers published in the past and in this century (e.g., Němejc 1937; Pešek 2004, 2005). Until now, the duration of this hiatus has only been the subject of speculation. However, it was probably a longer break in sedimentation as indicated by, among other things, the fact that, with the exception of local areas, nearly the entire upper part of the Radnice Member, including the Lubná seams, is absent in the Plzeň Basin or by the fact that, for example, in the former mines Důl Obránců míru and Důl v Týnci in the Plzeň region, the basal clastic rocks of the Nýřany Member lie directly on the Upper Radnice Seam, which was locally partially or completely eroded (Fig. 7). In addition, the logs of some boreholes in the Kladno area (e.g., Bř 1 and 2 near Beřovice, Br 5 near Třebusice) suggest that a larger section or even the entire upper part of the Radnice Member was eroded during the hiatus. The study of the palaeosol in this unit indicates several stages in the development of vertisols, which had to take at least several tens of thousands of years to form (Opluštil et al. 2015). When Opluštil et al. (2016) dated the detrital zircons in the volcanogenic interlayers of all formations, they also documented, among other things, the age of the Kladno Formation and determined the duration of the hiatus between the Radnice and Nýřany members (about 3.6 Ma), which reflects the Leonian Phase of the Variscan Orogeny. Their research suggests that as many as several hundred metres of deposits of the Radnice Member may have been eroded prior to the deposition of the Nýřany Member.

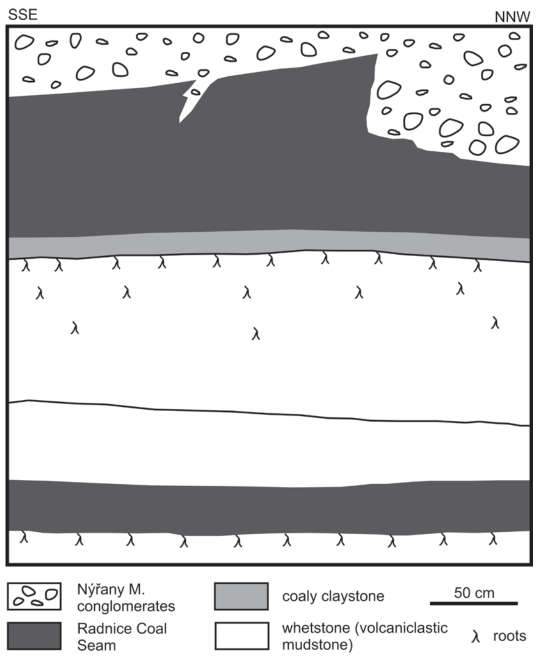

Fig. 7. Erosion of the Upper Radnice Coal Seam. Former Mine Obránců míru, Plzeň Basin. From Pešek (1978).

Significant tectonic reorganization of the Central and Western Bohemian basins occurred during the break in sedimentation between the Radnice and Nýřany members. For example, in the Plzeň Basin, the depocentres changed significantly (Fig. 3). They were elongated in a NNE–SSW direction during the deposition of the sediments of the Radnice Member, but they are oriented in a NW–SE direction in the Nýřany Member. Few boreholes have explored the sediments of these units in the Kladno–Rakovník Basin, so that definite conclusions cannot be made here. In the major part of the Mšeno–Roudnice Basin, sedimentation began in the Nýřany Member.

Nýřany Member

The sediments of the Nýřany Member, of Asturian to Cantabrian (Late Moscovian to Early Kasimovian) age, occur in all Central and Western Bohemian basins and also in some Pennsylvanian relics, which flank these basins. In this unit, subarkoses and mostly grey siltstones and claystones dominate over tuffs, tuffites and seams occasionally up to 2.5 m thick. A northward fining of sediments is noticeable in the Central Bohemian basins (see App. VIII in Pešek 1994). The deposits of the Nýřany Member cover a substantially larger area than the preceding unit. They occur in the entire area of the Plzeň Basin, cover more than half of the Manětín and Žihle basins, and most of the area of the Kladno–Rakovník and Mšeno–Roudnice basins. They occur locally in the Radnice area as well. They are also known from a number of Pennsylvanian relics, particularly west of the Plzeň and Manětín basins. The varying age of the basal sediments of this unit, for example, in the Plzeň area and the Mšeno–Roudnice Basin indicates a gradual onset of their deposition.

Plzeň Basin

During the break in sedimentation between the Radnice and Nýřany members, significant changes occurred in the structure of the Central and Western Bohemian basins (see above). Due to the relatively detailed exploration of the Plzeň Basin, it is possible to reliably clarify its tectonic reconstruction. The central depocentre was still active in the basin and, in addition, four NW–SE oriented tectonically predisposed individual depocentres separated by narrow horsts were formed. While the average thickness of the Nýřany Member is less than 290 m in the Plzeň Basin, it is a several tens of metres greater in the synsedimentary central depocentre. The sediments of this unit are also thicker in the NW–SE oriented structures (Fig. 3), the most prominent of which is the depocentre in the south of the basin.

Kladno–Rakovník and Mšeno–Roudnice basins

Despite the fact that a large number of boreholes were drilled into the basement in both basins (several hundred in the Kladno–Rakovník Basin and about 60 in the Mšeno–Roudnice Basin), the level of knowledge regarding the tectonic evolution of these basins during the deposition of the Nýřany Member is slightly lower in comparison with the Plzeň Basin. However, it is very likely that similar changes occurred in the Central Bohemian basins as in the Plzeň Basin. The Zlonice–Peruc depocentre (see above) undoubtedly remained active even though the trend of the axis of this depocentre differs somewhat from that of the Radnice Member (Fig. 8). Its activity is indicated by a significant increase in the sediment thickness of this unit. The average thickness of the mostly grey sediments of the Nýřany Member is about 335 m in the Kladno–Rakovník area, whereas their verified thickness in this structure is greater than 500 m. A further increase in thickness in a NW–SE direction, albeit considerably smaller in comparison with the Zlonice–Peruc depocentre, is evident in an area northwest of Rakovník. It cannot be excluded that this is a narrow tectonically predisposed depocentre.

A relatively considerable decline in the thickness of the sediments of the Nýřany Member is noticeable to the east in the Mšeno–Roudnice Basin. While the average thickness of the Nýřany Member in the Roudnice (western) part of this basin is about 170 m, it decreases below 100 m in the Mšeno (eastern) part of the basin. This decline is probably related to the subsequent onset of sedimentation in this part of the basin (see above). In both of these basins, the axes of the depocentres of the Nýřany Member are clearly oriented in a roughly E–W or ENE–WSW direction, which may be considered as the oldest reflection of terrestrial sedimentation of the reactivation of main basin boundary faults governing the sedimentation along the structure of the Variscan Arc of the Bohemian Massif (Havlena & Pešek 1980).

Hiatus between the Nýřany Member and the Týnec Formation

The notion that a hiatus occurred between these two units was first expressed by Wagner (1977) based on a study of flora. Its existence was also considered by Havlena & Pešek (1980) based on further spreading of the sediments of the Týnec Formation over the crystalline basement, and the

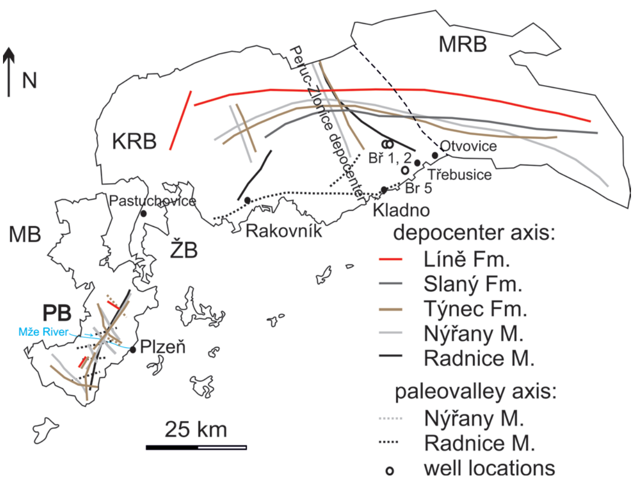

Fig. 8. Major depocentre axes showing shifts of maximum subsidence areas.

"... formation of a single Central Bohemian–Sudetic sedimentation area ..., and the connection of the thus far independently developing sedimentary basins ...", namely the Central and Western Bohemian basins on one side and the Sudetic (Lusatian) basins on the other. The break in sedimentation between the Nýřany Member and the Týnec Formation is also indicated by occurrences of relatively massive conglomerate beds at the base of the Týnec Formation in the Plzeň area. During this hiatus, or prior to the deposition of the sediments of the Týnec Formation, the tectonic movements that occurred may not have been strong or they occurred rather locally because the average dip of the siltstones of the Nýřany Member and Týnec Formation differs by only 2 degrees (Fig. 4b). However, the weathered rocks at the top of the Nýřany Member that were identified from the descriptions of drill cores, for example, from boreholes Je 1, MB 3, 6, 7, 20, ŘP 1, Vs 1 and Vůj 1 from the Mšeno-Roudnice Basin (Fig. 5) may provide evidence of the break in sedimentation. In borehole Je 1, the weathered rocks at the top of the Nýřany Member were up to about 15 m thick. The existence of this hiatus and its duration of 1.8 Ma was clearly documented by Opluštil et al. (2016).

Týnec Formation

The sediments of the Týnec Formation, of Barruelian to Lower Saberian (Kasimovian) age, occur in all the Central and Western Bohemian basins with the exception of the Radnice Basin. Their thickness varies in individual basins due to the varying subsidence rate of the basement. The deposits of this unit are occasionally preserved in the Pennsylvanian relics near several basins. However, the sediments of this unit do not differ much petrographically from the preceding unit. By contrast, the usually pronounced red colours of mudstones are distinctive for this unit. Beds of whitish conglomerates and dark green mottled siltstones and claystones occur relatively frequently in the Plzeň Basin. In comparison to the Nýřany Member, the volcanic products and coals in the Central and Western Bohemian basins occur rarely in the Týnec Formation. Carbonate concretions occur more or less frequently, with abundant occurrences mainly at the top of this unit.

Plzeň Basin

The Týnec Formation was preserved in this basin only in the central depocentre and in transverse NW–SE oriented grabens that originated and were apparently still weakly subsiding (Fig. 3). This is indicated by a slight increase in the thickness of the deposits of the Týnec Formation in these structures, in which they are up to 125 m thick, while their average thickness slightly exceeds only 110 m in the entire basin.

Kladno–Rakovník and Mšeno–Roudnice basins

The sediments of the Týnec Formation fill roughly the same area as the preceding unit, since they are absent particularly at the western and eastern margins of the Rakovník part of the Kladno–Rakovník Basin. Locally, however, they slightly extend beyond the preceding unit and lie on the Neoproterozoic basement. They are, however, absent along the entire southern margin of the Central Bohemian basins, where this unit was eroded. The average thickness of the sediments of the Týnec Formation is about 175 m in the area of Kladno–Rakovník Basin and probably 125 m in the Mšeno–Roudnice Basin. However, mudstones occur more often in the Mšeno–Roudnice Basin than in the Kladno-Rakovník Basin. The Třtěno–Zlonice depocentre was active in the Týnec Formation in the east of the Kladno–Rakovník Basin, where the deposits of this unit were up to 245 m thick, and a NW–SE oriented depocentre was also active in an area north of Rakovník with a roughly 200 m thick fill. In both of these basins, the E–W axis of maximum subsidence more or less follows a similar structure of the Nýřany Member (Fig. 8).

Hiatus between the Týnec and Slaný formations

A short-term, local rather than basin-wide break in sedimentation between the two formations (Pešek 1994) cannot be ruled out due to local differences in the thickness and other characteristics of the Jelenice Member (the basal unit of the Slaný Formation). The unit reaches a thickness of more than 100 m of predominantly coarse conglomerates, in borehole Kbl 2 in the Mšeno–Roudnice Basin southeast of Mělník. By contrast, the sediments of this member are only about 10 m thick in the Plzeň Basin. This notion is also supported, among other things, by the occurrence of numerous carbonate concretions and signs of weathering (Fig. 5) at the top of the sediments of the Týnec Formation (e.g., boreholes KV 1 and MJ 8 in the Mšeno–Roudnice Basin) and also by slight differences in the average dip of the siltstones of both units, for example, in the boreholes in the Mšeno–Roudnice Basin (only two degrees, Fig. 4b). A hiatus duration of less than 1 Ma may be inferred from the dating of volcaniclastic horizons (Opluštil et al. 2016) assuming that the sedimentation rate for the Týnec Formation is similar to that of the other units.

Slaný Formation

The deposits of the Slaný Formation, of Saberian (Gzhelian) age, are known from all Central and Western Bohemian basins with the exception of the Radnice Basin. The petrographic characteristics of the basal unit, the Jelenice Member, do not differ much from those of the sediments of the underlying formation. There is a difference mainly in the colour of the mudstones, which are mostly grey and in which a locally up to more than 4 m thick bituminous coal seam occurs in the majority of boreholes primarily in the Mšeno–Roudnice Basin. One to two coal seams mostly less than 1 m thick were discovered at the top of this unit in the Plzeň Basin and in the Central Bohemian basins. Numerous volcaniclastic layers mostly only a few cm thick, which suggest the resumption of volcanic activity in source areas or which by contrast to the preceding unit were better preserved due to a suitable environment, occur in the Slaný Formation mainly in the Central Bohemian basins.

A specific feature of this unit is the formation of an extensive intrabasinal lake during the deposition of the sediments of the Malesice Member, which probably extended well beyond its present southern margin to the south in the Plzeň Basin. In the east, the lake extended into the Intra-Sudetic Basin, or even further northeastward into Poland through the Mnichovo Hradiště and Krkonoše Piedmont basins. Previous notions that the sediments of this unit were deposited in a relatively tranquil environment are probably not entirely correct. It cannot be ruled out that the deposition of the Malesice Member may have been, as indicated by geological and geophysical studies in the Mšeno–Roudnice Basin, interrupted locally or across a wider area several times (e.g., Bosák 1989; Žbánek et al. 1990a, b; Pešek 1994 and Lojka et al. 2014). An angular unconformity was also reported in this unit in a man-made exposure of the sediments of the Hředle Member east of the village of Pastuchovice in the Kladno–Rakovník Basin (Lojka et al. 2014).

Plzeň Basin

The Slaný Formation was preserved in this basin only in the central depocentre and in transverse grabens. However, it cannot be clearly demonstrated that these structures were still active during the deposition of the sediments of this formation. The average thickness of the deposits of the Slaný Formation is nearly 180 m. Despite the fact that only the remains of the unit were preserved in this basin, a different, coarser, peripheral development of the sediments of the Slaný Formation was confirmed by several boreholes (e.g., near the villages of Chotíkov and Tlučná) on the western as well as the eastern basin margin (Havlena & Pešek 1980).

Kladno–Rakovník and Mšeno–Roudnice basins

As in the case of the preceding Kladno and Týnec formations, it is appropriate to characterize the deposits of the Slaný Formation regarding both basins together. The sediments of this formation fill roughly the same area as the preceding unit, but they slightly exceed its extent to the north and lie on the Neoproterozoic basement. However, in comparison to the Týnec Formation, they are absent over a much larger area along the entire southern margin of the Central Bohemian basins, where they were eroded during the Permian or even later. The average thickness of these sediments is around 175 m in the Kladno–Rakovník area and about 125 m in the Mšeno–Roudnice Basin. As in the Týnec Formation, the subsidence axis in this unit is also oriented approximately in an E–W direction. The trend of isopachs clearly shows that the thickness of the sediments of the Slaný Formation decreases northward. By contrast, a significant increase in the thickness of the deposits of this unit was documented in the Central Bohemian basins in the Slaný area north of Kladno, and also the Mšeno–Roudnice Basin in the wider surroundings of Mělník, near Všetaty and Benátky nad Jizerou (Pešek 1994).

Figures 4a and b clearly show the different dips and dip directions of the mudstone beds of the Líně Formation, dipping gently (ca. 6 degrees) northeast. While the sediments of Slaný and Kladno formations dip steeply (ca. 10 degrees) mostly to the southwest (Svrčinová in Žbánek et al. 1990a, b; Bosák 1991).

Hiatus between the Slaný and Líně formations

The break in sedimentation between these two units is associated with the Intra-Stephanian phase of the Variscan Orogeny, which took place in most of the terrestrial basins of the Czech Republic. Significant changes in source areas, for example, the formation of new basins — the Blanice and Boskovice grabens are also associated with this phase. The existence of the hiatus between the Slaný and Líně formations is also indicated by the change of average dip of the mudstones between these two units (four degrees difference), by the sediments of the Slaný Formation that were locally eroded down to the Hředle Member (Fig. 6), by signs of weathering at the top of the preserved deposits of the Slaný Formation (Fig. 5), and also by the different characteristics and colours of the sediments of these two units (see below). By reinterpreting the seismic measurements of Kadlečík et al. (1985, 1990), Skopec et al. (e.g., 1990, 2001) a roughly E–W direction of a nearly 100 m deep river valley with several smaller tributaries was discovered. Figure 6 clearly shows that the above-mentioned stream flowed from the east or east-southeast to the west, where in the boreholes in the east of the Mšeno–Roudnice Basin it even eroded down into the Hředle Member and all its overlying layers (i.e. the Ledec and Kounov members). This palaeo-stream probably flowed further westward, where the original thickness of the sediments of the Hředle Member is preserved and where only the thickness of the Kounov Member partially declines in the east of this basin. The occurrence of weathered rocks of the uppermost part of the Slaný Formation below the erosional surface of the Líně and Slaný formations clearly demonstrates that the weathering of the preserved deposits did not take place until after their erosion (Fig. 5). The shift of the depocentre from the south to the north is also very significant (Fig. 8). The duration of this hiatus can be estimated at about 1 Ma based on the dating of volcaniclastic horizons (Opluštil et al. 2016).

Líně Formation

The deposits of the Líně Formation, of Stephanian C to Autunian (Late Gzhelian to Asselian) age (Opluštil et al. 2016), occur in all the Central and Western Bohemian basins with the exception of the Radnice Basin. However, there are significant, possibly primary, depositional differences in the thickness of this unit in individual basins. The average thickness of the Líně Formation is less than 50 m in the Plzeň Basin, but it reaches about 245 m and nearly 500 m in the Kladno–Rakovník Basin and Mšeno–Roudnice Basin, respectively. The maximum thickness of the deposits of this unit (over 1000 m) was verified in the Rakovník part of the

Kladno–Rakovník Basin in the Žatec area north of Rakovník. The Líně Formation is mostly dominated by red-coloured mudstones with green circular spots. One so-called grey horizon occurs in the formation in the Kladno–Rakovník Basin, whereas up to three such horizons were discovered in the Mšeno–Roudnice Basin. A bituminous coal seam up to several tens of centimetres thick occurs in the bottom and middle horizons. Numerous carbonate concretions, in which many mostly thin volcanogenic intercalations were discovered, formed in the entire complex.

Plzeň Basin

The sediments of this unit were preserved in the Plzeň Basin only at the intersection of the NNE–SSW oriented central depocentre and in some NW–SE oriented transverse grabens. While the occurrence of the sediments was verified only in three small relics north of the Mže River (northern basin half), the largest area that they fill is located in the south of the basin north of the village of Líně and east of the town of Nýřany (see Dopita et al. 1985). By contrast to the Central and Western Bohemian basins, the Plzeň Basin does not contain any grey horizons or volcanogenic intercalations (see below) because only a small thickness of the Líně Formation was preserved.

Kladno–Rakovník and Mšeno–Roudnice basins

As in the case of the preceding units, the sediments of the Líně Formation were characterized regarding both basins together. The sediments of the formation fill roughly the same area as the preceding unit. However, they were verified also in the west and north of the Kladno–Rakovník Basin, where they locally overlie the Neoproterozoic basement. In the east of the Mšeno–Roudnice Basin, Zikmundová & Holub (1965) discovered an occurrence of conglomerates with pebbles of the Barrandian type, which have thus far not been found in any other lithostratigraphic unit. Breccias with a clayey matrix that are thus far also not known in the older units of the Central Bohemian basins occur at the northern margin of this basin.

As in the case of both preceding units, the subsidence axis in the Líně Formation has an approximately E–W orientation as well. However, unlike in the preceding units, it has shifted northward (Fig. 8). In addition, a significant increase in the thickness of the deposits of this formation is noticeable in a NNE–SSW oriented depocentre in the west of the Rakovník part of the Kladno–Rakovník Basin. According to Elznic et al. (1974), the orientation of this structure is similar to the elongation of the central depocentre of the Plzeň Basin. An increase in the thickness of Tertiary clastic rocks in the Žatec area north of Rakovník suggests that this structure was apparently active later on as well.

Hiatuses in the Líně Formation

By reinterpreting seismic profiles in the Mšeno–Roudnice Basin, Skopec et al. (2001) discovered several river valleys at around 100, 200 and 300 m above the base of this unit. It can be presumed that, at these levels, a local break in sedimentation occurred and that hitherto unknown river valley up to more than 100 m deep were formed. They were oriented in a roughly E–W direction that is more or less identical to the direction of the main stream, which erodes the uppermost lithostratigraphic units of the Slaný Formation. These valleys were filled with mostly coarse clastic sediments.

Discussion and conclusions

The activity of fault structures and deep fault zones oriented mainly in a NE–SW and NW–SE directions led to the formation of the Western and Central Bohemian basins. Our work as well as a number of previous studies, for example, by Havlena & Pešek (1980), Pešek (1994) and Pešek et al. (1998) suggest that, throughout the filling of the Western and Central Bohemian basins, the Central Bohemian Fault Zone was considerably active and that the Litoměřice Fault, or also the Jáchymov Fault, gradually became more active as well. Their activity is indicated by the quantity and quality of the material transported into these basins, primarily into the Central Bohemian basins from the south, north and west. The greatest amount of clastic rocks were undoubtedly transported from the south. The northward shifting of the depocentres of the units of the Central Bohemian basins is related to the continuous uplift of the southern source area, so that the Nýřany Member and all other subsequent units do not have a peripheral but more or less mid-basin position.

The tectonic evolution of the Plzeň and Central Bohemian basins was completely different, with the exception of the Radnice Member. The sediments of this unit were deposited in the central depocentre in the Plzeň Basin and in the NNE–SSW oriented Rakovník depocentre as well as in NE–SW oriented depressions. The latter are very likely morphological depressions, which formed due to the differential erosion of weakly metamorphosed Neoproterozoic shales, greywackes as well as palaeobasalts and their tuffs. These depressions are generally very productive. They contain several-metre-thick bituminous coal seams accompanied mostly by mudstones and volcaniclastic rocks only a few metres to a few tens of metres thick. By contrast, the origin of the central depocentre in the Plzeň Basin remains unclear. It cannot be excluded that it was originally an old river valley of unknown age. The more than 250 m thickness of the non-coal-bearing mostly coarse clastic rocks of this unit, the increase in the thickness of other units, and the postsedimentary recurrence of movements in this structure clearly demonstrate that this structure was repeatedly tectonically active.

The geological structure of the Plzeň Basin has two dominant features, the central depocentre with a NNE–SSW direction, in which also the sediments of the Líně Formation, among others, were locally preserved and the roughly NW–SE oriented transverse grabens, separated by narrow horsts. The sediments of the Slaný Formation occur in these transverse grabens and also locally in the central depocentre in areas where the deposits of the Líně Formation were not preserved. In both cases, these are tectonically active synsedimentary and postsedimentary structures, which is demonstrated by an increase in the thickness of their fill when compared with the thickness of deposits of the same age located outside these depocentres. In view of the fact that only the sediments of Týnec Formation were preserved in several transverse grabens, it is evident that the movements in these transverse structures were undoubtedly younger than in the central depocentre.

The Kladno–Rakovník and Mšeno–Roudnice basins form a single accommodation space. The Kladno–Rakovník Basin, for example, shares specific common features with the Plzeň Basin with regard to the formation of the basal unit, the Radnice Member. By contrast, the deposits of this unit are absent in the Mšeno–Roudnice Basin with the exception of minor areas. In addition, a NNE–SSW oriented depression filled mainly with coarse-grained clastic sediments more than 260 m thick was discovered north of Rakovník in the Kladno–Rakovník Basin. However, a significant increase in the thickness of the deposits of younger units was not found. It is therefore possible that this is only the fill of an erosional valley, which was however no longer tectonically active later on. An erosional valley oriented in a roughly NNE–SSW direction exists in the Kladno–Rakovník Basin as well. However, given the extent of the basin, it is considerably longer than the length of morphological depressions in the Plzeň Basin. The tectonically predisposed and undoubtedly repeatedly active NW–SE oriented Zlonice–Peruc depocentre is completely different. In this structure, the thickness of the Radnice and Nýřany members and also that of the Týnec Formation increases considerably. In the Nýřany Member and Týnec Formation, a NW–SE oriented structure was active in the area north of Rakovník as well. This is indicated by an increase in the thickness of the deposits of these units in comparison with the surroundings. While being more or less identical in the Nýřany Member and in the Týnec and Slaný formations, the axis of maximum subsidence is shifted northward in the Líně Formation. This change is probably related to significant changes in the evolution of the basins and source areas caused by the Intra-Stephanian phase of the Variscan Orogeny and apparently also by the uplift of the core of the Bohemian Massif. A NNE–SSW oriented structure, which lies in the elongation of the central depocentre of the Plzeň Basin to the north, was active in the west of the Kladno–Rakovník Basin as well. Unlike the Plzeň Basin, this structure was still active in the Miocene as indicated by an increase in its sedimentary fill during this period in the North Bohemian Basin.

Two hiatuses associated with a major shift of the depocentres between the Radnice and Nýřany members and between the Slaný and Líně formations are interpreted here as being the product of the tectonic reorganization of the basins. By contrast, hiatuses below and above the Týnec Formation, where substantial changes in depocentres did not occur and where carbonate cementation was discovered in addition to fossil weathering products, are interpreted as being mainly climatically driven (comp. Roscher & Schneider 2006). It is very likely that a stronger climate aridization occurred during this period, which could have slowed down the input of clastic sediments into the basins and so may have caused the hiatuses. This is supported by the characteristics of the sediments of the Týnec Formation (a predominance of red fine-grained clastic rocks, abundance of carbonate cementation, a poor preservation of fossils), by correlation with other Central European basins, and also by climate models for this period (Roscher & Schneider 2006; Roscher et al. 2008).

In view of the characteristics of the Líně Formation, we presume that both tectonic and climatic changes occurred during the formation of the hiatus between the Slaný and Líně formations, where the severe effects of climate aridization are clearly evident. This hiatus corresponds to the Early Gzhelian dry phase of Roscher & Schneider (2006), which could be traced across the European Late Palaeozoic basins. But there is also evidence for tectonic activity in the region, for example, in the Saale and Saar-Nahe basins thick red bed sediments were deposited during this interval. In the case of the Saale Basin a strong tectonic event with basin reorganization is indicated between the Rothenburg and Siebigerode formations (Schneider et al. 2005, 2006; Schneider & Romer 2010), approximately at the level of the hiatus between the Slaný and Líně formations.

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