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Mykhailo MATROFAILO

Institute of Geology and Geochemistry of Combustible Minerals of NAS Ukraine, 3a, Naukova str., Lviv, 79060, Ukraine, tel. +38(032) 2632541, e-mail: mmatrofaylo@gmail.com, https://orcid.org/0000-0002-4175-6037

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STAGES OF GEODYNAMIC DEVELOPMENT OF THE LVIV–VOLYN COAL BASIN

The purpose of this work is to analyze geodynamic processes of origination, geological development, and Post-Carboniferous alteration of Carboniferous deposits of the Lviv–Volyn Basin. The methodology is based on historical-geological and facies studies. It includes a comparison of the capacities and distribution of deposits of different ages in the region as well as a dynamic analysis of the formation of coal deposits in the basin. The conducted investigations showed that the territory of the Lviv–Volyn Basin had a special history of geostructural Pre-Carboniferous development that sufficiently influenced its formation and caused geotectonic and morpho-structural alterations. The formation of this region resulted from complex and prolonged, during several tectonic stages, processes of interaction between the zones of tectonic activity and regional fractures connected with it. Activation of these zones happened to be at definite periods of geological time and was manifested in the development of concrete geostructural elements. Tectonic events of all periods of sedimentary cover formation were individual and unique. They became the basis for the formation and changes in the overall structure of the southwestern edge of the East European Platform and, in particular, the Lviv–Volyn Basin, as part of the Lviv–Lublin Trough. With other geostructural relations, the tectonic structure of the basin would be significantly different. In the Paleozoic era, the structural elements of the north-western and south-eastern extension played a decisive role in the formation of this territory. Originality. Based on the analysis of the thickness of the region's deposits of different ages it was shown that forces of horizontal compression affected the coal-bearing unit during the geological formation of the basin. During their influence, there was a depression of the territory, which led to the formation of primary tectonic forms and Post-Carboniferous main tectonic and morphological structures. The coal-bearing deposits have undergone repeated wash-outs, resulting in a shortening of the section and a significant decrease in the volume of the productive part of the coal formation.There is a graphic representation of the change dynamics in the location of crystalline basement surface at different stages of tectonic formation of sedimentary thickness of the basin, whose inclination was different. Practical significance. The conducted research determined stage-by-stage geodynamic development of the territory of the Lviv–Volyn Basin. Five distinct stages can be identified in the formation of coal-bearing deposits, from their origin to their eventual erosion. These stages reflect the unique features of coal formation and geodynamic processes. The geological map of the Pre-Mesozoic deposits of the carboniferous coal-bearing megaformation in the Lviv–Lublin Basin provides insight into the geological structure of the Lviv–Volyn and Lublin Basins, highlighting both similarities and differences. These findings contribute to our understanding of the formation processes of Carboniferous coal-bearing formation in the Lviv–Volyn Basin. They also expand our knowledge of coal distribution, coal seam morphology, and coal thickness structure, which can be used to compare with coal-bearing formations in other basins.

Key words: faults; crystalline basement; Carboniferous; tectonic movements; stages of geodynamic development, Paleozoic depression; Lviv–Volyn Coal Basin.

Introduction

The formation of coal basins is one of the regional geological processes that occurred cyclically with a favourable ratio of tectonic, climatic, geomorphological, phytocenological, and other factors. The great eras of coal formation refer to the periods of slow oscillatory movements of the earth's crust against the background of the general long-term submergence of large areas. It should be noted that in the middle of the Paleozoic era, carbon-forming plants that thrived in moist environments were primarily limited to coastal plains where organic matter could accumulate. However, more suitable conditions for the formation and development of plant life were widespread on the ancient northern continent of Laurasia in the Northern Hemisphere. This is consistent with the modern location map of coal basins and deposits of the world [Energetics..., 2005]. This found its mark in the emergence and spread of the main masses of higher plants, which reached us in the form of coal deposits, for example, within the limits of the Lviv–Lublin coal basin (LLB).

A large accumulation of organic matter, from which humic coal of industrial importance was formed in the territory of Ukraine, occurred in the

Carboniferous. The Lviv–Volyn Coal Basin (LVB) is located in the west of Ukraine, within the Lviv Paleozoic Trough (LPP). It is the southeastern extension of the Lviv–Lublin pericratonic trough, a large tectonic structure of the southwestern edge of the East European Platform [Dolenko et al., 1980, 1984; Krupskyi, 2001; Shulga et al., 2007; and others].

It should be noted that the first assumptions regarding the presence of coal deposits on the territory of the modern Lviv–Volyn basin were known at the beginning of the last century. Later, in 1935, on the basis of the discovery of the lower coal fauna and wells drilled in the Lviv Region in 1938, coal deposits with coal seams 0.5–0.9 m thick were discovered. The coal system deposits in Poland and Ukraine are part of a single sedimentary basin and form a large coal megaformation. These deposits lie on top of the eroded surface of sedimentary and volcanogenic-sedimentary formations from the Upper Proterozoic, Cambrian, Ordovician, Silurian, and Upper Devonian periods. These deposits have been uncovered by wells and partially by coal mine workings (Fig. 1) [Dembowski and Porzycki, 1988; State..., 2004; Shulga et al., 2007; Zdanowski, 2007; Kostyk et al., 2016].

The Lviv-Volyn coal basin extends in the submeridional direction for 190 km and has an average width of 60 km [Kostyk et al., 2016]. Its industrial development began in the fifties of the last century [Struev et al., 1984]. Since then, various organizations, scientific research institutions, and many researchers have carried out reconnaissance work, thematic and scientific research on issues of stratigraphy and lithology, tectonics, coal-bearing, morphology of coal seams, hydrogeology, coal quality and their classification, physical and mechanical properties of coal-bearing rocks, gas capacity of the productive layer, etc. [Bobrovnyk, 1960; Bobrovnyk et al., 1962; Kushniruk, 1967, 1968; Kushniruk and Bartoshinska, 1971; Feduschak et al., 1974; Vyrvych et al., 1978; Bartoshinskaya et al., 1983; Struev et al., 1984; Karavaev, 1987; Fedushchak and Radchenko, 1988; Kostyk et al., 2008; Shulga et al., 2008; Matrofailo, 2010; Bezruchko and Matrofailo, 2014; Bezruchko and Matrofailo, 2015; Kostyk et al., 2016; Shulga et al., 1992, 2007; and others].

The northern border of the basin coincides with the state border of the Republic of Belarus (see Fig. 1). In the northeast and south, it is bounded by a band of Visean limestones that extends through the villages of Zalissya, Verbivka, Zaturtsi, and the town of Horohiv, east of the town of Busk and south of the city of Lviv. In the southwest, the border runs along the line of the Rava-Ruska fault, and in the west, it coincides with the state border of Ukraine and Poland. The foot of the Carboniferous is located at depths from 139 to 2000 m within the boundaries of the Kariv and Tyagliv synclines.

The formation of the Carboniferous LVB is the area of development of coal-bearing deposits with coal seams of the lower (Tournaisian, Visean, and Serpukhiv layers – Viséan, Namurian A), as well as the middle (Lower Bashkirian layer – Namur B, C, Lower Westphalian A) division, which is located on the extreme in the west of Ukraine in the upper reaches of the W. Buh River (see Fig. 1, Fig. 2) [Shulga et al., 2007; Kostyk et al., 2008; Vdovenko et al., 2013; Bezruchko and Matrofailo, 2015; and etc.].

Carboniferous deposits form a paralic Lower-Middle Carboniferous coal-bearing formation, which is a complex polyfacies formation. It distinguishes three main groups of facies: mainly continental, transitional from continental to marine, and marine. It is composed mainly of terrigenous sediments (mudstones, siltstones, sandstones), limestones, coal, carbonaceous argillites and sapropelites (see Fig. 2). According to the structure, the degree of carbon content, and the conditions of formation of the Lower-Middle Carboniferous Formation of LVB, two subformations are distinguished [Shulga et al., 1992, 2007]. The lower part is represented by a marsh-marine regressive subformation. Its upper boundary, according to [Shulga et al., 2007], is drawn along the cover of the third Posidonia horizon of the PIII Lublin suite, and in its absence – along the cover of limestone N_4. It consists of deposits of the Visean, Serpukhovian layers and the Lublin suite. The upper part is an alluvial-swamp-lacustrine-lagoon regressive-transgressive industrial coal-bearing sub-formation consisting of rocks of the Bashkirian layer, except for the lower part of the Buzhan suite. The uppermost Carboniferous part of the LVB the Bashkirian Stage is absent [Vdovenko et al., 2013].

The deposits of the coal-bearing stratum have a general monoclinal occurrence and a gentle dip in the southwest direction at an angle of 1–5°. At the same time, the basin, in addition to the general regional inclination of Carboniferous deposits to the southwest, is characterized by the spread of disjunctive tectonic disturbances. The monoclinal dip is complicated by alternating synclinal and anticlinal zones of northwestern extension, within which the dip angles of rocks are 6–8°, and in the southwestern part of the LVB in the Zhovkva zone, the dip angles increase from 30 to 60–70° [Struev et al., 1984; Kostyk et al., 2016].

The Lublin Coal Basin (LB) is a continuation of the LVB and extends from the state border between Poland and Ukraine in the northwest direction through the town of Skierniewice and is located in the southeast of Poland [Dembowski and Porzycki, 1988] (see Fig. 1).

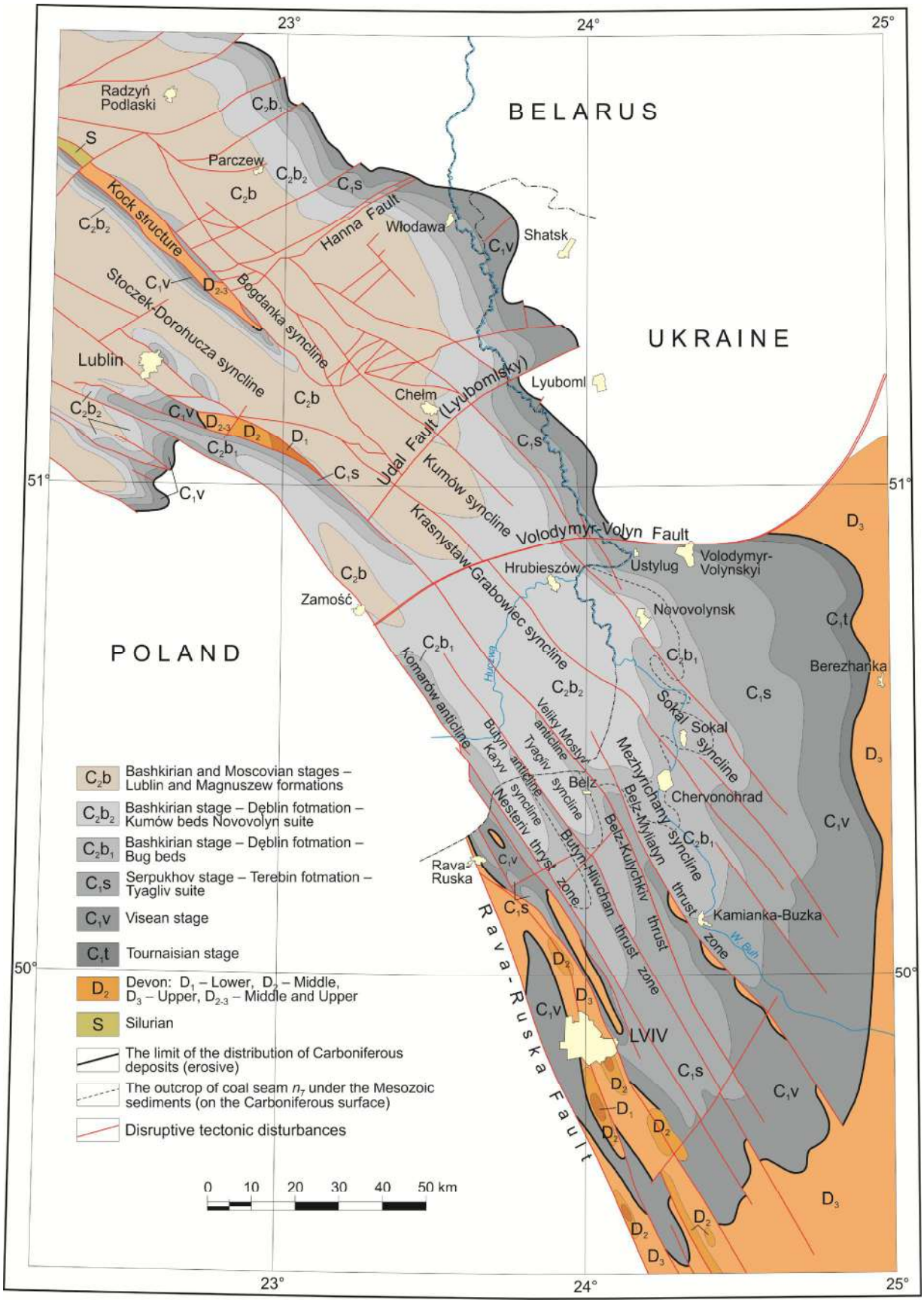

Fig. 1. Geological map of pre-Mesozoic sediments of the Lviv–Lublin coal basin with important tectonic structures (according to [Dembowski and Porzycki, 1988; State..., 2004; Shulga et al., 2007; Zdanowski, 2007; Kostyk et al., 2016]).

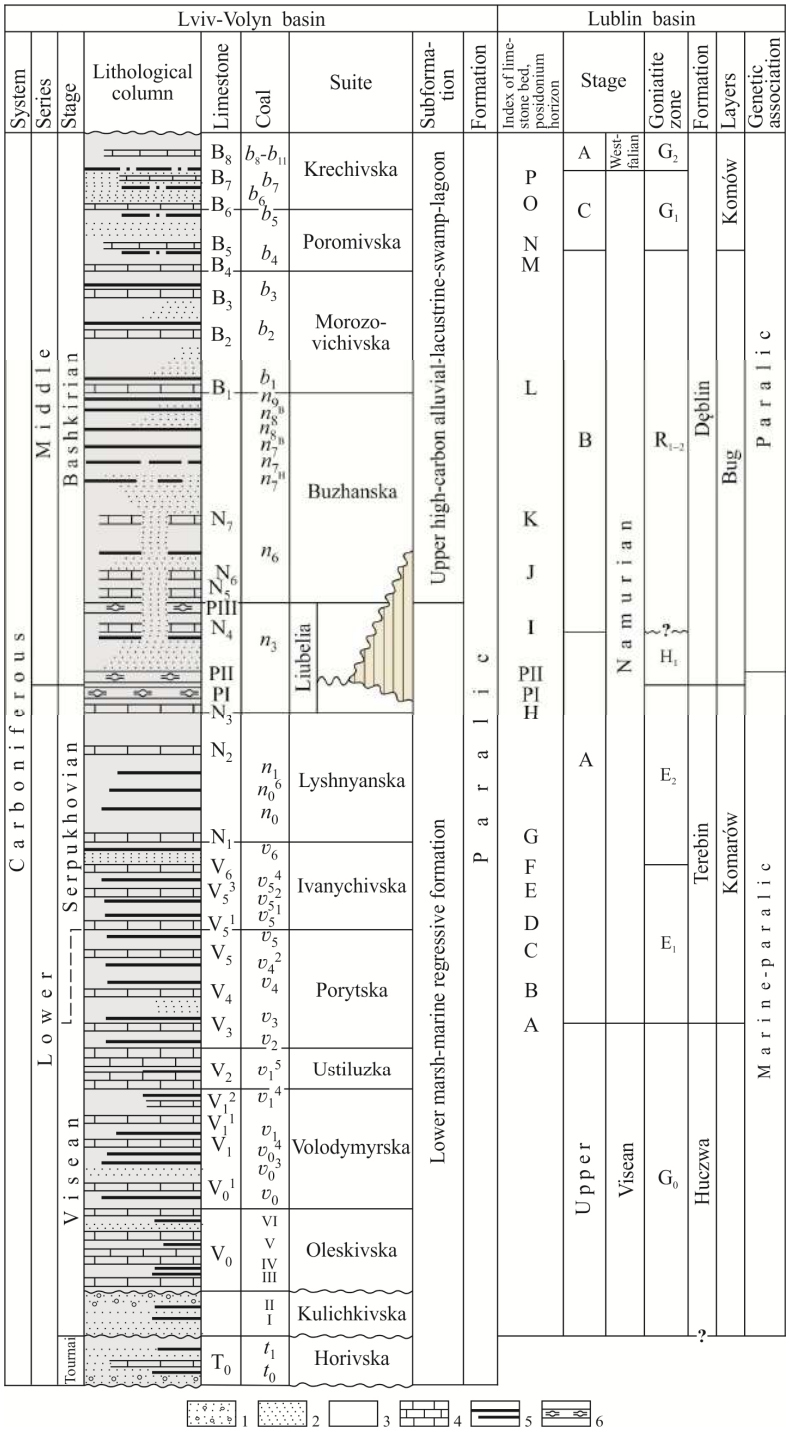

Fig. 2. Combined stratigraphic section of coal deposits and correlation of limestones and posidonium horizons in the border area of the Lviv–Volyn and Lublin coal basins (according to [Shulga et al., 2007; Kostyk et al., 2008; Vdovenko et al., 2013]):

1 – gravelite, conglomerate; 2 – sandstone; 3 – siltstone, argillite; 4 – limestone; 5 – coal seams and layers; 6 – Posidonia horizon: RI, PII, PIII. The lower boundary of the LVB coal-bearing formation is shown according to [Kostyk et al. ., 2008, 2016].

Carboniferous deposits were first discovered in the Lublin district even before the Second World War. In the years 1954–1961, systematic prospecting and exploration work was carried out by geological organizations in the territory of the Lublin Province, which culminated in the discovery of the large Lublin Coal Basin [Struev et al., 1984; Dembowski and Porzycki, 1988; Zdanowski and Żakowa, 1995]. As a result of the study of geological sections of the wells, it was established that coal deposits of the same age, known in the LVB, as well as younger industrial coal-bearing deposits of the Middle Carboniferous lie in a large area of Eastern Poland.

Fundamental geological studies conducted in 1964–1971 established a productive Westphalian and associated coal deposits. According to its geological features, the coal-bearing area of LB is divided into northern and southern parts. The southern part of the basin is characterized by lower sedimentation capacity and lower carbon content. In the north, the thickness of the coal-bearing stratum increases with the simultaneous expansion of the Middle Carboniferous section by younger layers, which are characterized by increased coal bearing. The main one is the northern part of LB, where significant reserves of coal were discovered [Dembowski and Porzycki, 1967; Porzycki, 1978; Struev et al., 1984]. Numerous geological and geophysical studies have been conducted on the basin since its discovery. These studies have focused on various aspects such as stratigraphy, lithology, sedimentology, petrography, carbon content, coal quality, hydrogeology, and gas content of the productive stratum. Additionally, radiometric studies have been conducted on the age of volcanic rocks present in the lower parts of carbon deposits. Overall, these studies have contributed significantly to our understanding of the basin's characteristics and potential [Żelichowski, 1972, 1979; Żelichowski and Kozłowski, 1983; Porzycki, 1979, 1988; Kaczyñski, 1984; Musiał and Tabor, 1988; Dembowski and Porzycki, 1988; Skompski, 1996, 2011; Narkiewicz et al. 1998; Zdanowski, 2007; Krzywiec, 2007, 2009; Pańczyk and Nawrocki, 2015; Krzywiec et al. 2017; Tomaszczyk and Jarosiñski, 2017; Jureczka et al. 2019; Waksmundzka, 2012, 2013; Kozłowska and Waksmundzka, 2020; Waksmundzka et al. 2021; etc.].

The Lublin coal basin is located on the southwestern edge of the East European (Precambrian) platform at its junction with the young West European (Paleozoic). LB is a pericratonic basin that was formed as a result of depression in the suture zone of the platform edge [Shulga et al., 2007]. The boundaries of the LB are defined by pre-Mesozoic outcrops of coal deposits, bounded from the north and southwest by fault zones (see Fig. 1). The area of the basin is more than 11.000 km^2 [Zdanowski, 2007].

The thickness of the coal seam increases to the southwest. The smallest thickness of about 100 m is observed in the northeastern part of the basin, where the elevated part of the East European Platform lies in the basement. Larger thicknesses, from several hundred metres to 2000 m, are characteristic of deposits in the rest of the basin, within the boundaries of the Masovian-Lublin basin [Żelichowski, 1972; Żelichowski and Kozłowski, 1983].

According to [Dembowski and Porzycki, 1988], in the Carboniferous in the territory of LB, the palaeogeography of the Tournaisian and Lower Visean, Upper Visean, Namurian A, Namurian B–C, Westphalian A–B and Westphalian C was studied. Based on biostratigraphic data, the age of the youngest deposits of the Upper Carboniferous was determined as Westphalian D (?) [Musiał and Tabor, 1988; Porzycki and Zdanowski, 1995]. At the same time, based on the determination of the age of the basalts of the lower part of the coal deposits, it is shown that the oldest rocks of the basin belong to the late Tournaisian [Pańczyk and Nawrocki, 2015]. In general, according to the international stratigraphic scale, the Carboniferous of the Lublin Basin is represented by sediments from the Upper Tournaisian to the Lower Moscovian stage [Waksmundzka, 2013].

Carboniferous LB formations are composed of argillites, siltstones, sandstones, conglomerates, limestones, marls, stigmarium layers, carbonaceous argillites, layers and layers of coal. The lower part of the section sometimes contains volcanites and bauxites [Musiał and Tabor, 1988; Skompski, 1996; Zdanowski, 2007; Waksmundzka, 2012, 2013; Pańczyk and Nawrocki, 2015; Waksmundzka et al. 2021; etc.].

Coal seams and layers in the LLB coal-bearing megaformation, in general, lie in deposits from the Tournai to the Moscovian stage of the Middle Carboniferous (Westphalian C, D?) [Dembowski and Porzycki, 1988; Shulga et al., 2007; Kostyk et al., 2016; etc]. The thickness of coal seams ranges from 0.05 to 4 m. Industrial coal seams of the Lublin basin are common in the Terebin, Dęblin (lower and upper sub-formations of the LVB) and Lublin, which is absent in the LVB due to post-Carboniferous erosion. The main productive coal seams are common in the Lublin strata, the thickness of which increases from several tens to 900 m. Stratigraphically, they belong to the Westphalian A–B. In this stratum, 24 balance coal seams with a thickness of 0.30–2.40 m are established [Porzycki, 1978]. At the same time, according to [Shulga et al., 2007], there are from 63 to 90 seams and layers of coal in the coal-bearing formation of the boundary part of the LLB. The total number of LB layers in the lower coal-bearing formation is 19, and 22 in the upper one.

In the LB, on the basis of the numerous marine, brackish-water, and freshwater fauna found, two genetic associations were distinguished: the lower – marine-paralic, the upper – paralic, which correspond to the sub-formations of the LB (see Fig. 2). At the same time, a paralic stratum, which includes the formation of the Upper Visean, Namurian, and Westphalian A, and a younger limnic stratum are distinguished in the coal deposits. The lower subdivisions of the sediments contain mainly marine fauna, the top of the section is dominated by sediments with brackish and freshwater fauna, and the youngest Carboniferous sediments do not contain fossils of macrofauna [Dembowski and Porzycki, 1988].

The Lublin coal basin lies on a stable foundation, which caused the predominance of block-thrust and fold-block tectonics [Porzycki, 1979, 1988]. Block-thrust tectonics prevails in the northeastern part of the LB, and fold-block tectonics prevails in the southwestern part. These parts are separated by the horst-anticlinal structure of Kock and further to the southeast by faults [Żelichowski, 1972, 1979; Dembowski and Porzycki, 1988; etc.].

The sediments of the marginal zone of the northeastern part are slightly inclined to the southwest and further form a large asymmetric syncline, the axis of

which extends from the northwest to the southeast. The dip of the layers of its northeastern wing is 2–4º, and the southwestern one is 12–17°, which transitions into the Kock horst anticlinal structure. The southwestern part of the LB is characterized by the spread of anticlinal uplifts of northwest and southeast trends, separated by synclinal dips. Both parts of the LB are broken by two systems of northeast and southwest thrusts, which cross the Carboniferous across the length of the basin, and northwest and southeast thrusts, located along the length of the basin. The southwestern part of the basin is characterized by more complex tectonics [Żelichowski, 1972, 1979; Dembowski and Porzycki, 1988; etc.].

The development of subsidence in the basin was controlled by shear movements along the Teisseyre-Tornquist zone in the extensional regime [Żelichowski, 1987; Narkiewicz et al. 1998].

In the structure of the Lublin basin, the differentiation of the basement of the Late Paleozoic cover was of primary importance. It determined the zonal structure of the coal-bearing formation, which manifested itself in the zonal contours of the isopachites of the Carboniferous subdivisions, the distribution of lithofacies, the nature of the diagenesis of rocks, etc. The modern tectonic model of the basin, the formation of which was largely influenced by the structure of the basement, was formed during the Asturian phase of tectogenesis, after the deposition of Westphalian D [Porzycki, 1979; Zelichowski, 1972, 1979; Dembowski and Porzycki, 1988; etc.].

Purpose of work

The purpose of this work is to analyse geodynamic processes of origination, geological development, and Post-Carboniferous alteration of Carboniferous deposits of the Lviv–Volyn Basin.

Method

The methodology is based on complex historical-geological and facies studies and includes the analysis of the distribution and capacities of sediments of different ages in the region and the dynamic analysis of the formation of Carboniferous deposits in the basin. When studying the Lviv–Volyn basin, the method of formation analysis was applied It has a complex nature and, in particular, includes palaeoreconstructions of coal-bearing deposits. Its main provisions were developed during the study of the coal-bearing formations of the Donetsk and other basins and are presented in works [Vasilyev, 1950; Lomashov, 1958; Zhemchuzhnikov et al., 1959, 1960; Shulga, 1962; Shulga et al., 1992, 2007; and etc.].

Results

Geostructural position of the research area on the map of paleocontinents and oceans during the Carboniferous

The sequence of changes in the geostructural position of the territory of the Lviv–Volyn coal basin is determined by the geological stages of the global (Fig. 3) [Golonka, 2000] from the Late Devonian to the Late Carboniferous and the regional (Fig. 4) development of Western Ukraine, where the LVB is located [Medvedev, 1979; Pavlyuk et al., 2006].

The evolution of the region during the geological time of the formation of the coal basin, which is shown in a concise form in the figures, allows us to get an idea of the sequence of the main tectonic events, their age, formation, and location in the general structure of the southwestern edge of the East European Platform. In particular, during the Carboniferous period, the convergence of the continents, which took place from the Late Devonian, can be traced. Wide accumulation of phytomass occurred mainly in the humid conditions of the equatorial belt, which stretched across North America and Europe in a powerful band. At the same time, in the Late Carboniferous, the southern regions of the East European Platform occupied a near-equatorial (between 0–5° and 15–20°) latitudinal position. In contrast to the ancient position, the modern LVB is located in the northern hemisphere between 49° and 52° and has a northwesterly direction [Senkovsky and Demchenko, 1988].

Historical aspect of the development of the LVB territory

The area where the LVB is located has a lengthy history of geological development that began before the Carboniferous period. This resulted in the creation of favorable conditions for the formation and growth of the LVB. After the Carboniferous period, the area underwent significant geological and structural changes that played a role in its overall development. According to [Medvedev, 1979; Boyko et al., 2001; Pavlyuk et al., 2006; Pavlyuk et al., 2009; and others] the existence and development of this region is the result of a complex and long process (several tectonic cycles) of the interaction of zones of tectonic activation and associated regional faults of the diagonal system – the oldest in the region. The activation of these zones occurred during certain periods of geological time and was expressed in the development of specific geostructural elements, both longitudinal and transverse (pericratonic depressions, aulacogenes, uplifts and depressions).

Volyn-Podillia is a part of the Baltic-Black Sea pericraton. It is characterized by a complex structure and was formed during the Baikalian (R_3), Caledonian (V–D_1) and Variscan (D_2–P) tectonic stages, forming the final pre-Alpine structure of the territory of Western Ukraine and partly in Poland. Structures characteristic only of this period were formed on each of them. On the basis of the formational analysis of the sedimentary layer and on the basis of morphogenetic features, the following structures are distinguished here: the Volyn-Orsha Baikalian transverse marginal depression; Caledonian marginal system as part of the Baltic-Black Sea pericratonic trough (V–D_1^1) and Boyanetsky (D_1^{2-3}) foothills; Lviv–Lublin Variscan post-posthumous foreland (D_2–C_2) [Pavlyuk et al., 2006].

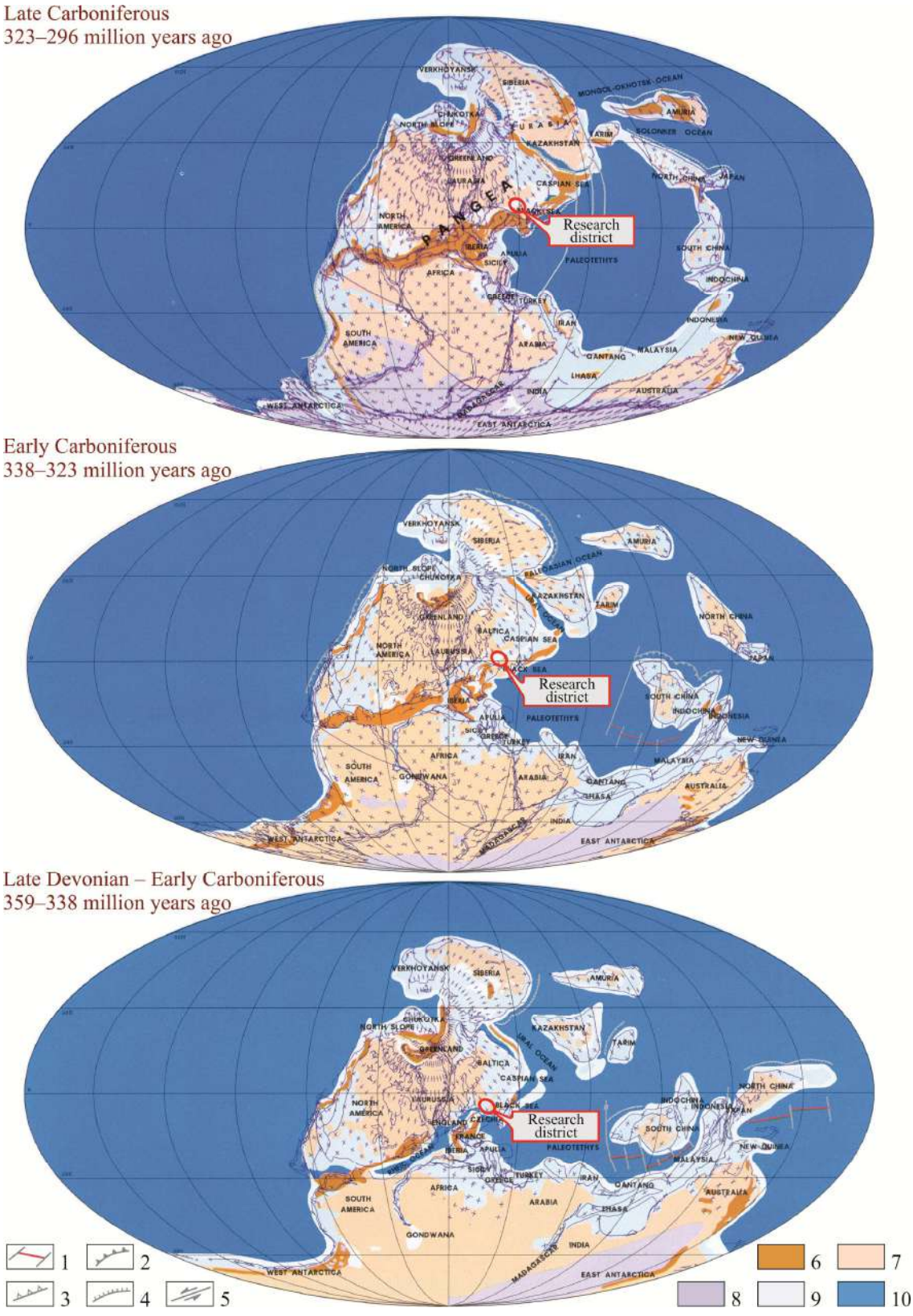

Fig. 3. Tectonic maps of the geodynamic evolution of the continents during the Late Devonian – Early Carboniferous (Kaskaskia III – 359–338 million years ago), Early Carboniferous (Kaskaskia IV – 338–323 million years ago) and Late Carboniferous (Early Absaroka I – 323–296 million years ago) years ago) (according to [Golonka, 2000]):

1 – oceanic spreading centres and transform faults; 2 – active subduction zones; 3 – thrusts; 4 – active or important normal faults; 5 – faults with strike-slip displacement; 6 – mountains; 7 – land; 8 – glaciers; 9 – shelf and slope; 10 – ocean.

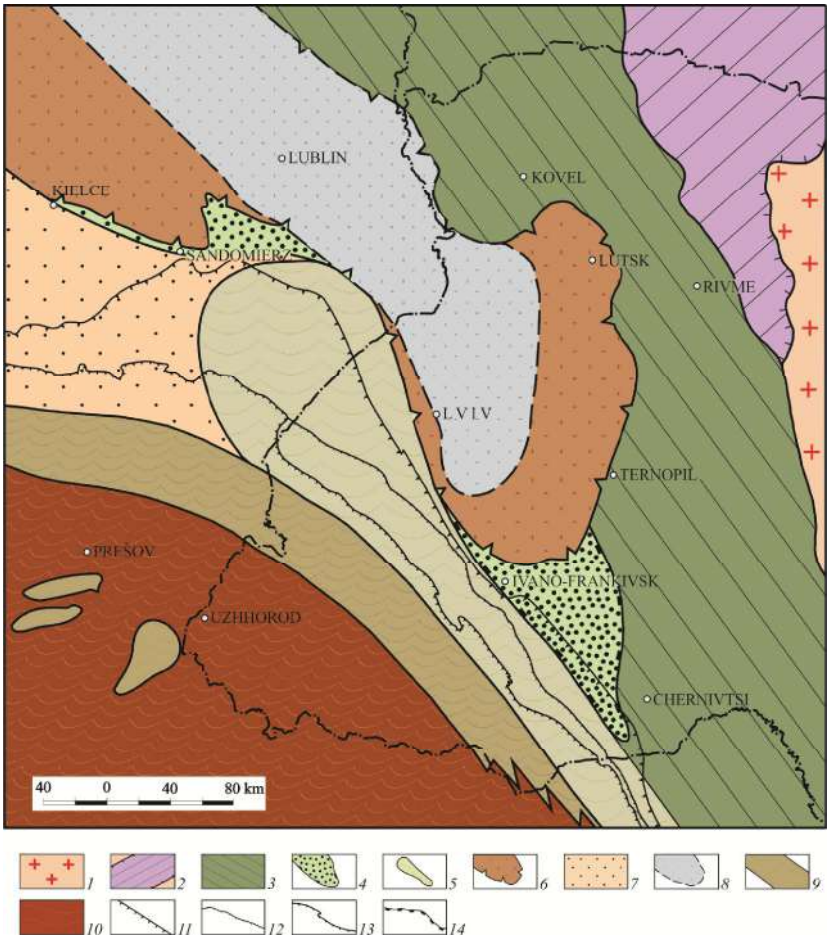

Fig. 4. The Variscan stage of forming the pre-Alpine structure of Volyn–Podillia and adjacent territories. Orogenic stage (Late Carboniferous-Permian) (according to [Medvedev, 1979; Pavlyuk et al., 2006]):

1 – the basement of the East European Platform; 2 – Baikalian transverse depression (Volyn–Orsha); 3–4 – Caledonian marginal system: 3 – pericratonic depression (Volyn-Podillia section of the Baltic-Black Sea pericraton), 4 – marginal (pedestrian) depression (Boyanetsky); 5 – pre-Variscan folded complexes (Variscan marginal platform uplift); 6 – Variscan post-posthumous fore-thrust (Lviv–Lyublin); 7 – Epicaledonian platform (Mekhuv depression); 8 – coal basin of paralic and limnic sediment accumulation in the post-humming fore-thrust (Lviv–Lyublin); 9 – molasse deposits of the Variscan marginal (foothill) depression and internal depressions; 10 – Variscan mountain-fold structure; 11–14 – contours of Alpine elements: 11 – Outer zone of the Precarpathian depression; 12 – Internal zone of the Precarpathian depression (Stebnyk thrust); 13 – Carpathian Overthrust; 14 – Transcarpathian depression.

The Lviv–Lublin region has experienced the greatest activation in the Paleozoic. In its formation in the geodynamic aspect, the structural elements of the northwestern and southeastern extension – the Baltic-Black Sea pericraton and the Volyn-Orsha avlacogen – play a decisive role. Within the pericraton, the surface of the crystalline Archean-Proterozoic basement is inclined to the west and southwest and dips east along the faults under the sedimentary cover, composed of deposits of the Upper Proterozoic (Riphean, Vendian), Paleozoic (Cambrian, Ordovician, Silurian, Devonian, Carboniferous), Mesozoic (Jurassic, Cretaceous), Cenozoic (Paleogene, Neogäikum). Its modern structure was formed during the Neogene under the influence of geodynamic processes that occurred on the edge of the East European Platform and in the adjacent Mediterranean mobile belt, and in particular, in its component – the Carpathians. In some parts of the southwestern edge of the East European Platform (Volyn-Podillia), this formation had its own peculiarities ([Geotectonics..., 1990; Pavlyuk et al., 2004; Pavlyuk et al., 2006], etc.).

Stages of geodynamic development of the Lviv–Volyn basin

During the Cambrian-Silurian period, vertical tectonic movements and a geodynamic stretching regime prevailed on the edge of the platform, which contributed to the development of discontinuous faults of the type of faults. According to [Geotectonics..., 1990], the block tectonics of the crystalline basement served as a framework for laying down Phanerozoic regional geostructures here. At the beginning of the Early Devonian, this tectonic regime changed to one dominated by compressive forces (Fig. 5, *a*). This

is connected with the final phases of folding of the Caledonian tectonic cycle and the red-colored continental formation (D_1^{2-3}) [Ryzun and Chizh, 1984].

It should be noted that at the border of the Lower and Middle Devonian, a restructuring of the structural plan is taking place, which is confirmed by a change in the dip angles of the rocks, and a change in the continental regime to the marine and lagoon regime. Downward movements are activated and the Lviv Paleozoic depression (LPP) is developing, which was actively formed in the Middle-Late Devonian (terrigenous-carbonate formation) and the Lower and Middle Carboniferous (coal-bearing formation) [Geotektonika..., 1990; Pavlyuk et al., 2006].

In the Late Devonian, most of the territory of Ukraine was covered by the sea. Mainly marine conditions existed, in particular, in the Lviv Paleozoic trough. Only from the end of the Famennian age, this territory was a raised land and was intensively eroded. This erosion and significant spread of marine conditions did not contribute to the development of coal formation processes both within the Lviv Trough and in the territory of Ukraine in the Devonian [Shulga et al., 2007].

During the Carboniferous period, there was a pause in sedimentation at the boundary between the Late Devonian (Famenian stage) and the Early Carboniferous (Tournaisian–Visean). As a result, the Lower and Middle Carboniferous carbonaceous formation was formed in the Lviv–Volyn basin. This formation is a part of the megaformation of the Lviv–Lublin basin (Fig. 5, *b*), which is divided into two sub-formations: the lower one being marsh-marine regressive, and the upper one being highly carbonaceous alluvial-swamp-lake-lagoon regressive-transgressive (see Fig. 2). [Shulga et al., 1992].

The initial stage of forming the coal-bearing formation (*Tournaisian-Early Visean*). Before the Carboniferous period, the territory underwent a transition to a continental mode of development. This was caused by the Bretonian phase of the Variscan orogeny, which resulted in repeated uplift of the territory during pre- and post-Tournaisian and Middle Visean times. This uplift caused regional and intraformational breaks in sediment accumulation. However, the short-term transgression of the sea in the Late Tournaisian caused the formation of a terrigenous carbonate stratum of rocks of the Khoriv suite [Bobrovnyk et al., 1962; Struev et al., 1984; Bartoshinskaya et al., 1983; Shulga et al., 2007; Kostyk et al., 2008; Vdovenko et al., 2013; and others].

It should be noted that at the base of the Khoriv suite lies a low-strength layer of limestone T_0, and layers of coal t_0 and t_1 and carbonaceous argillites with a thickness of up to 0.40 m were found in the argillites and siltstones of the upper and lower parts of the section [Kostyk et al., 2016]. In general, this indicates the existence of favourable conditions for the formation of palaeopeats in the territory of the LVB during the Tournaisian age. However, due to the significant dismemberment of the palaeorelief and the arid climate, the formation of small and weak palaeopeats occurred only in some isolated areas. The presence of layers of coal and carbonaceous argillites in the Khoriv suite clearly indicates the birth of a coal-bearing formation in the territory of the LVB, which continued to form during the long Carboniferous period. The late Tournaisian sediments correspond to the initial period of formation of the coal-bearing formation of LVB, and its lower boundary is argued to be along the sole of the Khoriv suite [Kostyk et al., 2008; Shulga et al., 2008; Kostyk et al., 2016].

In the Early Visean time, before the beginning of the Middle Visean, there was a continental break in the LPP, the land surface leveled off, and depressions were filled with sand-clay material of the Kulychkiv suite of the LVB. Compared to the Khoriv suite, it has a higher carbon capacity. Drilling determined the presence of coal seams and layers up to 0.50 m thick, as well as carbonaceous argillites up to 0.70 m thick in the world. Coal and carbonaceous argillites are located in the middle and upper parts of the world section, which are distinguished by a high content of kaolinite crumbly and semi-crumbly clays (argillites). The most stable in the section are coal seams I and II [Kostyk et al., 2008].

At the same time, in the Lublin depression during the period of activation of tectonic processes and interruptions in sedimentation during the Tournaisian-Early Visean stage, volcanic activity took place with the formation of basalt covers. They are located in the deposits of the lower part of the Carboniferous period, in particular, in the north-east of the Lublin basin, the alkaline basalts belong to the Late Tournaisian stage (348±0.8 million years), with a possible extension to the Middle Visean. During this period, physical and chemical weathering occurred in the territory of the LLB, which caused the leveling of the relief of the basin and the formation of the weathering crust [Shulga et al., 1992; Dembowski and Porzycki, 1988; Pańczyk and Nawrocki, 2015; Waksmundzka et al. 2021; and others]. The following downward movements of the basin territory led to extensive marine transgression at the end of the Middle Visean (the beginning of the second half of the Visean) and the formation of shallow water, mainly carbonate sediments in the central and southern parts of the LVB of the Olesko suite with numerous and diverse fauna, which indicates the spread of shallow-marine environments with stable sedimentary conditions. In the north of the basin, mainly terrigenous rocks (siltstones, mudstones), occasionally limestones with a small fauna and admixtures of terrigenous material were deposited, which indicates the development of conditions of an active hydrodynamic regime of the shallow sea [Bartoshinskaya et al., 1983; Struev et al., 1984; Shulga et al., 2007; Shulga et al., 2012; and others].

In the section of the Olesko suite, limestones have a subordinate importance. The marking horizon V_0 is highlighted in the upper part of the suite. Also, more than seven low-capacity non-working seams and layers of coal with a thickness of up to 0.35 m and layers of carbonaceous argillites with a thickness of up to 0.50 m are widespread in the world. Most often, coal seams III, IV and V occur in the lower part of the section and VI in the upper part [Kostyk et al., 2016].

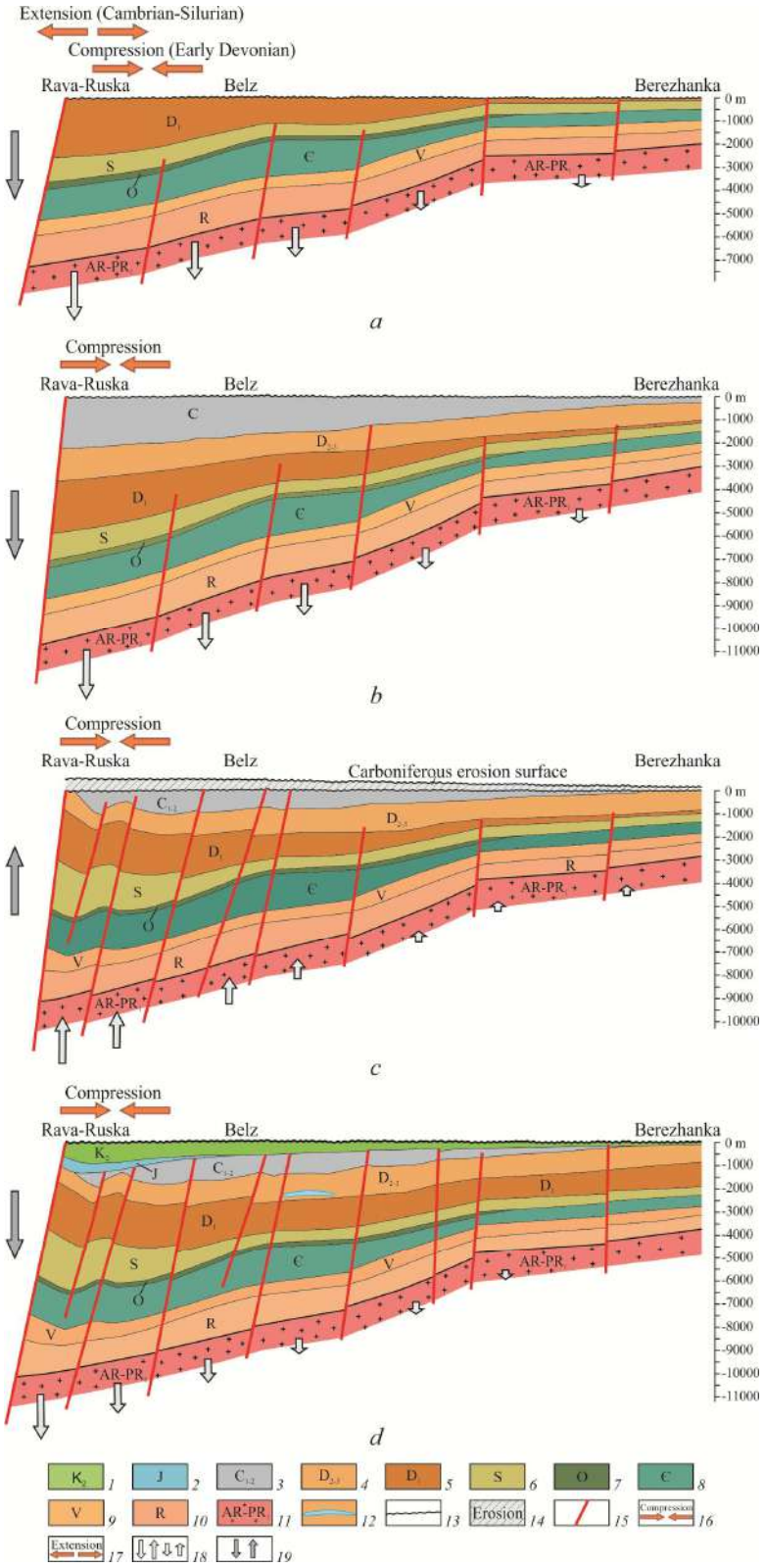

Fig. 5. Stages of geodynamic development of the territory of the Lviv–Volyn coal basin on the southwestern edge of the East European Platform:

1–11 – sedimentary formations: 1 – upper Cretaceous; 2 – Jurassic; 3 – Lower and Middle Carboniferous; 4, 5 Devonian: 4 – middle and upper; 5 – lower; 6 – Silurian; 7 – Ordovician; 8 – Cambrian; 9 – Vendian; 10 – Riphean; 11 – crystalline basement; 12 – gas deposit; 13 – erosion, angular and stratigraphic unconformities; 14 – erosion of Carboniferous deposits; 15 – discontinuous tectonic disturbances; 16–19 – geodynamic regimes: 16 – horizontal compression; 17 – horizontal tension; 18 – vertical and horizontal movements of basement blocks of different intensity; 19 – predominating directions of movement of the crystalline foundation and sedimentary layer completely.

Stage of non-industrial coal formation *(Late Visean-Late Serpukhovian).* The next stage of development of the LPP and coal-bearing formation of Lviv–Volyn, which began in the second half of the Middle and Late Visean, is characterized by a significant change in the tectonic regime, palaeogeographic conditions of sediment accumulation, composition, cyclic structure of the section, etc. Tectonic movements cover large areas, occur more often, and are characterized by lower contrast. This contributed to numerous transgressions and regressions of the sea and the development of marine conditions. Since Volodymyr time oscillating tectonic movements have been taking place, which contributed to a changing regime of sedimentation in coastal and transitional conditions. Short-term periods of elevation of the territory contributed to waterlogging, the accumulation of organic material and the formation of coal beds. Among the thick limestones V_0^1 – V_1^2 (V_1, $V_1^{1,}$ and V_1^2 – marking), calcareous argillites and sandy-clay rocks of the Volodymyr suite, coal seams and layers v_0–v_1^4 are widespread, of which only v_0^3 and v_0^4 in separate areas have working capacity, in particular, power v_0^3 in the Zabuzka deposit is 0.10–2.20 m. At the end of the Volodymyr time, the entire area of the basin was dominated by marine carbonate sedimentation. A similar regime existed in the Ustilug period, which is characterized by the formation of V_2 marking limestone, layers and two coal seams, in particular v_1^5, of non-working capacity (0.0–0.3 m). This layer is spread over individual small areas and has no industrial significance. The Volodymyr and Ustilug formations were accumulated during the largest transgression of the Visean Sea, which covered a large area, and their similar composition indicates the connection of the sedimentary basins of Europe and Asia [Bartoshinskaya et al., 1983; Struev et al., 1984; and others].

At the beginning of the Serpukhov period, the mode of deflection and conditions of the open sea in the territory of the basin were changed by upward movements. The accumulation of sediments took place in the conditions of a low sea coast, fluctuating tectonic regime and aridization of the climate. Transitional and continental conditions of sedimentation prevailed over marine ones. As a result, cyclic, mainly terrigenous deposits of the Porytsk and Ivanychiv suites were formed. With the gradual compensatory subsidence of the territory, there were periodic stable conditions of marine sedimentation of the shallow-water coastal zone, with the formation of limestones V_2^1 – V_5 of the Porytsk and V_5^1 – V_6 of the Ivanichiv suite, of which the V_6 layer has correlational value. Short-term uplift of the territory led to the emergence of swampy coastal plains and the formation of peatlands, from which thin coal seams and layers were formed in the future, in particular, v_2 – v_5 of Porytsk and v_5^1 – v_6 of Ivanychiv suite. Only the v_6 layer is of industrial importance over a larger area of the basin, with the exception of the Volyn field [Struev et al., 1984]. In the conditions of the manifestation of significant oscillatory movements, which determined short-term periods of drying, limestones were often formed in the roofs of low-power coal seams [Bartoshinskaya et al., 1983; Shulga et al., 1992].

The beginning of the formation of the Lishnyan suite (middle of the Serpukhovian time) is characterized by the deposition of marking limestone N_1 in the conditions of a short-term marine regime and higher mudstones with marine fauna. In general, the sediments of the Lishnyansk suite are dominated by the clayey type of sediments (argillites, siltstones), which indicates the low-lying contours of the sea shores and the significant leveling of the relief of the adjacent land areas, which were the source of the supply of terrigenous material [Bartoshinskaya et al., 1983; Struev et al., 1984;, etc.].

During the Lishnyan period, the sea basin shrinks and becomes shallower. Upward tectonic movements in the area of the Ukrainian Shield caused the general regression and retreat of the sea in the southwest direction. Continental sedimentary conditions are gradually expanding, and marine ones are shrinking. Therefore, favourable conditions for the formation of peatlands arose more and more often [Shulga et al., 2012]. In addition to the N_1 limestone, the N_2 limestone layer and low-power coal seams and layers n_0 – n_2^0 were formed during the accumulation of the Lishnyan suite. During the formation of the lower coal-bearing sub-formation, the width of the coal-forming zone was more than 200 km, and a certain decrease in coal-bearing capacity and replacement of peat layers within the sub-latitude belt in the central part of the basin occurred under the influence of the inherited Gorokhovo-Rivnen palaeohydrographic system [Shulga et al., 1992].

The stage of formation of thin coal seams of the Carboniferous LVB formation ended at the end of the Late Serpukhovian and the beginning of the Early Bashkir time. Since the late Serpukhovian age, the accumulative basin has been characterized by shallowing and desalination. At the same time, the intrusions of the sea caused the formation of argillaceous limestones N_3 and N_4, which are markers, and argillites of the three Posidonia horizons PI, PII, PIII of the Liubelia suite [Shulga et al., 2007; Shulga et al., 2012], and short-term elevation of the territory – low-power coal seams n_2^1, n_2^2, n_2^3, n_3 in separate areas. In general, this indicates a transition from predominantly marine and transitional to continental and transitional palaeogeographic settings, cyclical processes of sedimentation and a rapid change in regimes.

The stage of industrial coal formation *(Early Bashkirian).* The beginning of the stage is marked by the fact that during the Buzhanian period, the territory of the LVB underwent significant uplift and regression of the sea to the southwest, the spread of continental conditions, and a sharp increase in conditions favourable for waterlogging and peat-forming processes of sedimentation. Significant uplift of the territory is a consequence of the manifestation of the Sudeten phase of the Variscan orogenesis. In general, this tectonic cycle contributed to the accumulation of rhythmic intermediate continental and transitional continental to marine

sediments, which make up the Lower Bashkirian layer of the coal-bearing formation of the basin. During periods of uplift, the land was peneplainized and flat. In the conditions of wide marshy coastal lowlands and a favourable climate, a significant number of plant groups developed, which provided organic material for the formation of coal beds of industrial capacity [Bartoshinskaya et al., 1983; Struev et al., 1984; Shulga et al., 1992; Shulga, 2012; etc.].

The Buzhanian suite conformably rests on the deposits of the Liubelia suite and is also covered by the rocks of the Morozovichivsk suite. It belongs to the lower part of the Bashkirian stage and is widely developed on the LVB area. Its lower boundary is drawn along the cover of argillites of the third Posidonia horizon of the Liubelia suite, and in the absence of argillites and the layer of limestone N_4 – along the sole of the coal seam n_3, the upper – along the sole of the weathered limestone B_1 of the Morozovichivsk suite. It is composed of sandstones, among which mica ("silver sandstones"), layers of gravel sandstones and pebble conglomerates, siltstones and mudstones with layers of chemogenic limestones and layers of coal are characteristic. It is characterized by high coal content and the content of industrial coal seams [Shulga et al., 2007; Vdovenko et al., 2013].

In the Buzhanian suite there are marked limestones N_5, N_6, N_7, layers and layers of coal from n_5 to n_9, of which 8 are working ($n_7^{н}(n_7)$, $n_7(n_7^{1})$, $n_7^{в}$, n_8, n_8^{0}, $n_8^{в}$, n_8^{5}, n_9). Their thickness varies from 0.08–0.40 m to 0.10–0.82 m for non-working ones and from 0.10–1.49 m to 0.08–2.76 m (in single wells – up to 4.85 m) – for workers. Until recently, six coal seams – $n_7^{н}(n_7)$, $n_7(n_7^{1})$, $n_7^{в}$, n_8, $n_8^{в}$, and n_9 – were mined in the basin [Struev et al., 1984]. All of them are placed in the upper Buzhanian suite of the Bashkirian stage of the LVB and correspond to the Bug beds layers of the Dęblin Formation (Namurian B) of the Lublin Basin [Dembowski and Porzycki, 1988; Shulga et al., 2007].

The uneven subsidence of certain parts of the basin during the Buzhanian period caused heterogeneous sedimentation and led to lithological and facies heterogeneity and unequal strength of rocks, the formation of different types and genesis of cleavages, syngenetic and epigenetic intra-formation washouts, replacements, wedging of coal seams, etc. It should be noted that the peculiarities of the morphology and genesis of coal seams were determined by the interaction and multiple changes of palaeotectonic and palaeohydrographic factors and the significant influence of paleohydrographic systems [Shulga et al., 2007; Matrofailo, 2010; Bezruchko and Matrofailo, 2014, 2015].

During the Morozovichi and early Poromian times, there were downward movements and subsidence of the basin territory, which led to an increase in the transgression of the sea. During the formation of the Morozovichi and the lower part of the Poromivan suite, sedimentation took place in marine and transitional environments, and during the Late Poromivan – in continental and transitional ones. As a result, sediments of mainly terrigenous composition were formed. A certain distribution of dolomite layers in the Poromivan suite indicates aridization of the climate [Bartoshinskaya et al., 1983].

The Morozovychi suite conformably rests on the deposits of the Buzhanian suite and is overlain by the rocks of the Poromivan suite [Vdovenko et al., 2013]. In its section, siltstones and sandstones predominate, and mudstones are of subordinate importance. There are three layers of limestones $B_1(N_{10})$, $B_2(N_{11})$, and $B_3(N_{12})$ in the rock layer, of which only the lower B_1 is stable in the section over most of the territory. Limestones B_2 and B_3 are weak and unstable. Limestones belong to shallow coastal marine facies. In the composition of the world, there is a decrease in the carbon capacity and the development of facies of swampy coastal lowlands. Suite rocks include coal seams and layers $b_1(n_{10})$ – $b_3^{2}(n_{12}^{2})$, of which only b^{1}, b_2, b_3 have working capacity in individual deposits and can be of practical importance. Coal seams and layers are often replaced by terrigenous rocks, mainly sandstones.

The Poromivan suite is composed of sandstones, siltstones, occasionally argillites that lie in the cover of limestones, layers of coal and limestones $B_4(B_1)$ and $B_5(B_2)$, which are markers. Quartz sandstones, sometimes quartzite-like, prevail in the upper part of the section. The world contains six coal seams, the main mass of which is of low thickness (0.09–0.50 m) and has a local distribution. Of them, only $b_4(b_1)$ and b_5 are well maintained in terms of area and have a working capacity (0.10–1.99 m) in separate mine fields and sections.

The sediments of the Krekhiv suite are according to the formations of the Poromivan suite. The processes of its formation took place, mainly, in continental conditions, and marine sediments were accumulated only at certain stages. It is composed of alluvial sandstones with numerous thin layers and layers of coal of autochthonous origin, less common layers of argillites and siltstones with the remains of fossil flora and freshwater fauna fossils, which indicates their continental origin in the conditions of lakes or desalinated lagoons. Limestones have a limited distribution.

In the cross-section of the Krekhiv suite, there are four low-strength limestone layers, of which only B_6 (B_3) has a correlative value, and 12 coal seams and seams, five of which are of non-working thickness (0.10–0.65 m) (b_7, b_8, b_9, b_{10} and b_{11}) are close together and belong to the upper part of the section. Coal seam b_6 lies among siltstones and mudstones in the lower part of the section, reaches its working capacity in some areas, and is often replaced by sandstones [Struev et al., 1984].

The diverse marine fauna and calcareous algae found in the marine sedimentary rocks of this stage testify to the restoration of the short-term connection of the LVB with the eastern and western marine basins of that time in the Late Bashkirian period. In general, the formations of the late Poromivan and Krekhiv periods are similar to the sediments of the Buzhanian period of the Bashkirian age in terms of lithologic and facies characteristics. According to the fossil flora-faunistic remains, the age

of the Krechiv suite is comparable to the Mospin $C_2^2(G)$ and Smolyaniniv $C_2^3(H)$ suites of the Donbas (Late Bashkirian sediments), with the middle part of the Kumov strata of the Lublin basin, as well as with most of the Cheremshan horizon of the SEP, which corresponds to the Westphalian A of the Western European scale [Bartoshinskaya et al., 1983].

The final stage of accumulation of Carboniferous coal-bearing deposits *(Late Bashkirian-Moscovian).* The section of the coal formations of the Lviv–Volyn Basin ends with deposits of the Krekhiv suite. However, these sediments did not end the processes of formation of carbonaceous sedimentation in the territory of the LB and, quite possibly, the LB.

According to a number of authors, the palaeogeographic conditions that existed in the Early Bashkirian period on the territory of the LVB and were favourable for the formation of peatlands continued, in particular, in the Late Bashkirian period [Bartoshinskaya et al., 1983; Shulga et al., 2007].

In general, the universal regression of the seas, which began in the Serpukhovian, was especially intensively manifested in the Middle and Late Carboniferous. At that time, there was a favourable tectonic regime, which had a compensatory nature of sedimentation, a humid climate, the marine water areas were gradually reduced, which led to the creation of favourable conditions for coal formation, an increase in the number and area of peatlands within the marshy coastal lowlands in the territory of the Donetsk Basin, DDZ and LLB, i.e. coal accumulation processes were expanding. At the same time, the connection of the Late Bashkirian Sea of the LVB with the eastern and western seas of that time continued periodically.

Thus, according to [Shulga, 2012], in the Don-Dnieper depression during the Late Bashkirian-Moscovian stage, there was a humid tropical climate, rich vegetation, and a favourable tectonic mode of sedimentation. Numerous peatlands were formed within the marshy deltaic coastal lowlands in large areas. The most favourable conditions for peat accumulation were widespread in Donbas. Powerful late Bashkirian and late Moscovian stages of industrial coal formation were established along this most coal-bearing section.

In the Lublin Basin, which is genetically united with the LVB, sedimentation processes also continued up to the Westphalian C and partly D (Moscovian Tier) – a series of the youngest Carboniferous formations (Magnuszew Formation). The main productive deposits of the Lublin strata, which were formed later than the Krechev sediments and lie on the Kumów strata from the bottom of the coal seam 399(301) (Westphalian A–B). The greatest thickness of the Lublin strata, which has been preserved in structural subsidence, is 740–900 m. They account for the maximum amount of coal deposits. There are about 50 beds and interlayers of humus coal with a thickness of 0.10–3.80 m, of which 24 are of industrial importance with a predominant thickness of 0.80–1.60 m, in some cases reaching 2.70 m. 92 % of the pool reserves. The youngest coal deposits with a thickness of up to 800 m are located in the Lublin strata and complete the section of the Carboniferous LB. Stratigraphically, they belong to the Westphalian C and, partly, to the Westphalian D, are common only in the west of the basin and in the structural depressions of its central part and are characterized by a slight distribution of plant deposits. The upper limit of these formations is erosional. Permian-Mesozoic sediments lie on them with a stratigraphic break and an angular unconformity. [Dembowski and Porzycki, 1988].

Thus, the processes of accumulation of Carboniferous coal-bearing deposits in the territory of the Lviv-Volyn coal basin and, importantly, coal formation continued at least until the end of the Middle Carboniferous, and the areas of distribution of primary Carboniferous formations were much larger than the modern limits of the basin.

The complete cessation of coal formation processes occurred at the end of the Carboniferous and is due to the activation of tectonic movements associated with the Asturian phase of the Variscan tectonic epoch. These global phenomena caused the general uplift of the territory and intensive regression of the sea, which turned the territory of the western part of Ukraine and southern Poland into dry land [Medvedev, 1979]. The activation of tectonic movements at the border of the Middle and Late Carboniferous (between the Westphalian and Stephanian) led to a decrease in the rate of deflection, a reduction in sea areas, an increase in climate aridization processes, a decrease in wetland areas, an increase in the growth of arid forms of vegetation and a decrease in the accumulation of phytomass volumes, i.e., the processes were completed by sedimentation of the Carboniferous megaformation of the Lviv–Lublin Basin.

Along with the influence of the palaeogeographic conditions of formation and changes of the LVB coal-bearing formation, processes caused by palaeogeographic factors – various movements of the earth's crust – took place. It should be emphasized that the Carboniferous coal formation of the basin was formed under the influence of consedimentary tectonic movements of various amplitude, which affected its structure, and significantly changed (eroded) in the post-Carboniferous period.

Tectonic transformations of the LVB began and continued simultaneously with the accumulation of coal deposits. Sedimentary downward tectonic movements, and more differentiated at the beginning of the Carboniferous, determined the heterogeneous and zonal structure of the LVB, the growth of the coal-bearing strata in the southwestern direction to the edge of the platform (non-uniform deflection), different conditions of occurrence, a clear cyclic structure of the formation, the characteristic distribution of industrial coal bearing in section (the upper part of the Buzhanian suite), the heterogeneity of the facies conditions of sedimentation and coal formation, syngenetic and epigenetic intra-formation erosion of coal-bearing deposits, which are associated with the activity of palaeohydrographic systems, splitting of coal seams, metamorphism of coal,

which changes in the southwest direction from marks ДГ, Г (Volynske, Zabuzke deposits) to Ж, К (Liubelske deposit) in the direction of an increase in the capacity of coal-bearing deposits and the deflection of the basin, etc.

On the border of the Early and Late Carboniferous in the territory of the modern Carpathians, processes of fold formation and orogenesis took place with the formation of a mountain structure [Medvedev, 1979]. It is quite certain that in the direction of the platform and the coal basin, the conditions of mountain formation created compressive forces, which during the Carboniferous period, to varying degrees, constantly influenced the formation of primary tectonic structures and, most importantly, the sedimentary bending of the LVB territory.

Post-sedimentary changes in the coal-bearing formation occurred at the end of the Variscan tectonic epoch. In the work [Medvedev, 1979], it is shown that the final tectonic movements of the adjacent fold-mountain region along the Rava-Ruska fault slightly pushed the crumpled formations onto the Lviv Paleozoic trough. The final phases of the Variscan folding determined the formation of the main tectonic forms in the Lviv–Volyn basin and contributed to the formation of linear folded structures in the southwestern part of the Lviv–Lublin depression, complicated by discontinuous tectonic disturbances (thrusts, thrusts, thrusts). The closure of the Lviv Paleozoic Trough occurred during the Asturian phase of Variscan folding.

Thus, the post-Carboniferous erosion of the coal-bearing formation was preceded by structural rearrangements and folding processes, which, under the influence of horizontal compression, determined the formation of the main tectonic forms of the Lviv–Volyn coal basin with a monoclinal and weakly folded structure.

Erosion of coal deposits of the basin *(post-Carboniferous).* The activation of Variscan tectonic movements, and the general uplift of the basin area, as a result of the uplift of the platform, led to its transformation into land and the establishment of continental conditions that persisted until the beginning of the Jurassic period. Upward tectonic movements and widespread regression of the sea prevailed. At the same time, the aridization of the climate intensified, which reached the point of changing the humid climate to arid in the Late Permian-Triassic period.

It should be emphasized that the coal-bearing formation was eroded repeatedly in the post-Carboniferous period. The erosion processes of coal deposits led to a reduction of the section of the coal-bearing strata, a significant decrease in the volume of the coal-bearing formation and industrial coal reserves, the movement (in the direction of reduction) of the limit of the distribution of coal-bearing formations and industrial coal bearing capacity, and the formation of the outline of the exit of industrial coal seams to the pre-Mesozoic, characteristic of LVB the surface

Thus, at the end of the Carboniferous and the beginning of the Permian, a large area of the region turned into an erosion-denudation area, and the coal formation, first of all, changed significantly due to its pre-Late Jurassic epigenetic erosion (Fig. 5, c). Erosion-denudation processes took place particularly intensively in the territory of the LVB, where the Carboniferous stratigraphic section of the basin lacks deposits younger than those of the Late Bashkirian (Westphalian A), and covered at least the eastern part of the LVB, where the youngest coal deposits of the Westphalian C and partially D are missing. In addition, the territory of the Ukrainian Shield was in an elevated position throughout the Carboniferous. Within its limits, in dryland conditions, intense weathering of rocks continued and denudation processes took place.

At the end of the Permian and at the beginning of the Triassic, a continental hiatus prevailed in large areas and the processes of destruction of the structures of the Variscan orogeny took place, which led to the emergence of mainly unfavourable conditions for coal accumulation and the completion of the formation of Paleozoic and large erosion of Carboniferous coal-bearing formations.

The correlation of Carboniferous formations with the overlying Permian LB sediments [Pokorski, 1971], Jurassic and Cretaceous LVB [Struev et al., 1984; Shulga et al., 2007] proves that the modern area of the industrial coal-bearing basin is only a part of the LLB coal-bearing megaformation. The boundaries of the distribution of LVB coal deposits, coal deposits and contours of coal seams of the basin are not sedimentogenic, but erosional and denudation, on which Jurassic and Cretaceous deposits, which are also separated by a stratigraphic break and angular unconformity, lie with a large break in sedimentation and a significant angular unconformity.

At the pre-Late Jurassic stage of erosion of coal-bearing sediments on the territory of the LVB, the surface of Carboniferous was a coastal accumulative lowland with a highly fragmented palaeorelief [Struev et al., 1984]. At that time, channel paleowatercourses were widespread, and there were lakes in the recesses of the palaeorelief. The surface of the pre-Jurassic palaeorelief had a gentle slope in the southwest direction.

According to [Shulga et al., 2007], in the territory of the Lviv–Volyn basin in the Early Oxfordian time, the height difference of the palaeorelief was at least 120 m, and the Chervonohrad–Novovolynsk palaeohighland existed within the boundaries of the Volyn, Zabuzian, and Mezhirichan deposits. A similar form of paleorelief is highlighted within the Kariv syncline in the southwestern part of the basin. Paleohighlands were surrounded by valleys and valley-like lowlands, within which there were paleowaterflows (right tributaries) of the powerfully branched Kamianka-Buzka-Horokhiv paleohydrographic system. It is noted that the destruction of coal-bearing deposits and coal seams during the Oxfordian period occurred under the influence of tectonic (dispersion of rocks within the Nesterivska and Butyn-Hlivchanska anticline zones) and erosion factors. It is shown that paleovalleys were formed above anticlinal structures, forming an inverted paleorelief. Such processes determined epigenetic pre-Late Jurassic erosive erosion of carbon deposits.

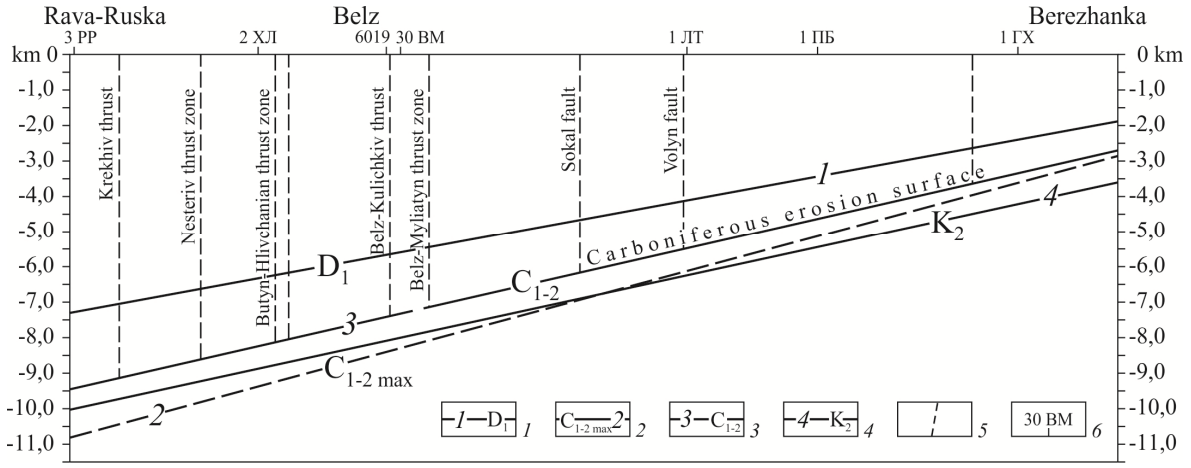

Fig. 6. Correlation of the location of the surface of the crystalline foundation at different stages of geodynamic development of the territory of the Lviv–Volyn coal basin of the southwestern slope of the East European platform:

1 – Early Devonian; 2 – Middle Carboniferous with the greatest thickness (before erosion); 3 – eroded deposits of the Middle Carboniferous; 4 – Late Cretaceous; 5 – main discontinuous tectonic disturbances; 6 – borehole and its number.

Further structural changes at the border of the Middle and Late Jurassic caused a wide surface deflection, which covered the territories of the East European Platform and the adjacent Carpathian geosyncline. During the Callovian-Oxfordian time, the intensity of depression of the depression gradually increased, the sea transgressed, and limestones, dolomites, and anhydrites originated on the continental formations [Struev et al., 1984]. The limits of marine sedimentation are increasing and the Stryi Jurassic trough is formed in the region of subsidence (Fig. 5, *d*), which extends to the territory of Poland. Its axis has a north-western extension. The Jurassic sediments also have a gentle southwest slope, filling the lower forms of the erosional Paleozoic relief in the basin. At the end of the Jurassic period, there was a significant universal regression of the sea.

During the Early Cretaceous period, significant denudation processes took place in the territory of the Lviv–Volyn Basin under continental conditions, which eroded the Jurassic and Carboniferous deposits.

The coal deposits of the Belz-Myliatyn anticlinal zone experienced the greatest erosion, where there is no industrial coal bearing between the Tyagliv and Mezhyrichan deposits, and the outline of the modern eastern border of the Volyn, Zabuzian, and Mezhyrichan deposits is due to the abrasion of the Cenomanian and Turonian seas [Shulga et al., 2007].

In the Late Cretaceous, after a short retreat, the transgression of the sea, which had a significant development in the Turonian and Coniacian ages, completely leveled the pre-Cretaceous surface. During the Maastrichtian period, there was a significant shortening and shallowing of the sea basin and the replacement of deep-water facies with shallow water. Later, the sea regresses and the Late Cretaceous surface is eroded.

As a result of the tectonic activity of the Carpathians in the Cretaceous period, a structural restructuring of the region took place and a Cretaceous depression was formed (see Fig. 5, *d*), where marine carbonate and carbonate-clay sediments accumulated. The Upper Cretaceous formations are spread over the entire southwestern edge of the East European Platform and cover the deposits of the Carboniferous and Jurassic systems with a thickness, completing the erosion of the LVB coal-bearing formation.

Post-Cretaceous discontinuous tectonic disturbances, formed as a result of Alpine tectonic movements in the Carpathian region, further complicated the occurrence and morphostructure of the coal deposits of the basin and negatively affected the industrial importance, the conditions for the development of coal seams and the completion of the formation of coal deposits of the LVB.

The sequence of the geostructural development of the region and the analysis of the capacities of its deposits of different ages allows us to form an idea about the dynamics and fluctuations of the surface of the crystalline basement at different geotectonic stages (Fig. 6). In general, during the long history of the geological development of the territory, descending vertical movements and geodynamic regimes of horizontally directed compression of different intensity and scale were of primary importance. Significant upward vertical movements took place, in particular, in the post-Carboniferous period and led to the erosion of the LVB coal-bearing formation (see Fig. 5, *c*). It should also be noted that the slope of the surface of the crystalline basement was different at different tectonic stages of the geostructural development of the region.

Originality

Based on the analysis of the thickness of the region's deposits of different ages it was shown that forces of horizontal compression affected the coal-bearing unit during the geological formation of the basin. During their influence, there was a depression of the territory,

which led to the formation of primary tectonic forms and Post-Carboniferous main tectonic and morphological structures. The coal-bearing deposits have undergone repeated wash-outs, resulting in a shortening of the section and a significant decrease in the volume of the productive part of the coal formation.There is a graphic representation of the change dynamics in the location of crystalline basement surface at different stages of tectonic formation of sedimentary thickness of the basin, whose inclination was different.

Practical significance

The conducted research determined stage-by-stage geodynamic development of the territory of the Lviv–Volyn Basin. Five distinct stages can be identified in the formation of coal-bearing deposits, from their origin to their eventual erosion. These stages reflect the unique features of coal formation and geodynamic processes. The geological map of the Pre-Mesozoic deposits of the carboniferous coal-bearing megaformation in the Lviv-Lublin Basin provides insight into the geological structure of the Lviv–Volyn and Lublin Basins, highlighting both similarities and differences. These findings contribute to our understanding of the formation processes of Carboniferous coal-bearing formation in the Lviv–Volyn Basin. They also expand our knowledge of coal distribution, coal seam morphology, and coal thickness structure, which can be used to compare with coal-bearing formations in other basins.

Conclusions

On the basis of the modern stratigraphic scheme of coal deposits of the Lviv Paleozoic Trough, we compiled a geological map of pre-Mesozoic deposits with important tectonic structures of the Carboniferous coal-bearing megaformation of the genetically unified Lviv–Lublin Basin, covering part of the southwestern slope of the East European Platform.

During the Carboniferous period, the Lviv–Volyn basin underwent rhythmic (pulsational) oscillatory movements that caused the deposition of a diverse range of sedimentary rocks. These include marine origin limestones, marls, and mudstones, as well as continental siltstones, sandstones, coal seams, carbonaceous mudstones, and sapropelites. Together, they formed a single coal-bearing formation within the basin. The periodic change in conditions of submergence and uplift of the LVB territory before its emergence to the day surface led to intra-formational regional breaks in sedimentation and syngenetic and epigenetic erosion of coal-bearing deposits, etc.

The processes of accumulation of Carboniferous coal-bearing deposits in the territory of the Lviv–Volyn coal basin and, importantly, coal formation continued at least until the end of the Middle Carboniferous, and the areas of distribution of primary Carboniferous formations were much larger than the modern boundaries of the basin.

During the entire period of the history of geological development and the post-Carboniferous stage of erosion of the coal formations of the Lviv–Volyn basin, the coal-bearing strata were constantly affected to varying degrees throughout the multi-stage history of tectonic movements, mainly by the forces of horizontal compression from the side of the tectonically active adjacent fold-mountain region. Under their influence, the compensatory sedimentation of the basin area and the formation of primary tectonic forms and post-Carboniferous main tectonic structures took place.

The post-Carboniferous erosion of the coal-bearing formation was preceded by structural rearrangements and folding processes. Under the influence of horizontal compression, this led to the formation of the main tectonic forms of the Lviv–Volyn coal basin with a monoclinal and weakly folded structure, complicated by discontinuous tectonic disturbances.

The geodynamic development of the territory of the Lviv–Volyn coal basin took place in stages. The formation of coal-bearing formations goes through such stages as nucleation (Tournai-Early Visean), non-industrial coal formation (Late Visean-Late Serpukhovian), industrial coal formation (Early Bashkirian), the final stage of accumulation of Carboniferous coal-bearing deposits (Late Bashkirian-Moscovian), and the erosion of coal deposits in the basin (Post-Carboniferous).

The Lviv–Volyn Coal Basin occupies the southeastern, most elevated marginal part of the large Lviv–Lublin Basin, where the post-coal bearing erosion-abrasive processes took place particularly intensively. This is explained by the absence of sediments younger than Late Bashkirian (Westphalian A) in the Carboniferous stratigraphic section.

The LVB coal deposits were significantly destroyed by intra-formational syngenetic (formed during the accumulation of coal-bearing strata) and post-Carboniferous regional epigenetic (secondary) erosions, which destroyed a significant part of the coal-bearing formation.

In the post-Carboniferous period, the coal seam was eroded repeatedly. The processes of erosion of coal deposits led to a reduction of the section, a significant decrease in the volume of coal-bearing formations and industrial coal reserves It also resulted in a movement (in the direction of reduction) of the limit of the distribution of coal-bearing formations and industrial coal capacity towards reduction. This led to the formation of a special wave-like outline of the limit of distribution of industrial coal capacity and the contour characteristic of LVB outcrop of working coal seams on the pre-Mesozoic surface, which is the cut contour of folds on the erosion surface.

The unique outline of the modern distribution area of coal-bearing deposits and the industrial coal-bearing in the LVB is due to the Asturian phase of folding in the adjacent areas and long-term erosion processes. These processes were influenced by pre-Upper Jurassic channel paleoflows and erosion-denudation in the Early

Cretaceous stage. They continued as abrasions during the continental regime and the transgression of the sea in the Cenomanian, Turonian and Coniacian ages of the Cretaceous period. The basin's extremely elevated location also played a role in the formation of this unique outline. As a result of several stages of post-Carboniferous genetically different erosion of the LVB coal deposits, only the platform part of the coal-bearing formation was preserved. Erosion processes took place from the beginning of the Permian to the Late Cretaceous. They overlapped with a continuous layer, in particular, the formations of the Carboniferous and Jurassic system with deposits of the Upper Cretaceous, completing the erosion of the LVB coal-bearing formation.

Alpine tectonic movements in the Carpathian region led to the formation of post-Cretaceous discontinuous tectonic disturbances. They complicated the occurrence and morphostructure of the coal deposits of the basin and negatively affected the industrial value, the conditions for the development of coal seams and the completion of the formation of coal deposits of the LVB.

A comparison is made and the dynamics of changes in the location of the surface of the crystalline basement in a cross-section at different tectonic stages of the formation of the sedimentary stratum and the erosion of the LVB coal-bearing formation are graphically shown. It is shown that the slope of the surface of the crystalline basement was different at different tectonic stages of the geostructural development of the region.

The study of the geological structure and analysis of the deposits of various ages in the region provides an improved understanding of coal deposits, the unique morphology of carbonaceous deposits, and is important for comparing the Lviv–Volyn coal-bearing formation with other coal-bearing basins of similar genesis.

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Михайло МАТРОФАЙЛО

Інститут геології і геохімії горючих копалин НАН України, вул. Наукова, 3а, Львів, 79060, Україна,
тел. +38(032)2632552, ел. пошта: mmatrofaylo@gmail.com, https://orcid.org/0000-0002-4175-6037

ЕТАПИ ГЕОДИНАМІЧНОГО РОЗВИТКУ ЛЬВІВСЬКО-ВОЛИНСЬКОГО КАМ'ЯНОВУГІЛЬНОГО БАСЕЙНУ

Мета роботи – аналіз геодинамічних процесів зародження, геологічного розвитку і післякарбонових змін кам'яновугільних відкладів Львівсько-Волинського басейну. Методика. Методика ґрунтується на комплексних історико-геологічних і фаціальних дослідженнях та передбачає зіставлення потужностей і поширення різновікових відкладів регіону та динамічний аналіз формування кам'яновугільних відкладів басейну. У результаті проведених досліджень показано, що територія сучасного розташування Львівсько-Волинського басейну мала особливу історію геоструктурного докарбонового розвитку, яка істотно вплинула на його формування і зумовила геотектонічні морфоструктурні зміни. Утворення цього регіону – результат складного і тривалого, упродовж декількох тектонічних етапів, процесу взаємодії зон тектонічної активізації та пов'язаних з нею регіональних розломів. Активізація цих зон припала на певні відліки геологічного часу та виражалася в розвитку конкретних геоструктурних елементів. Тектонічні події усіх періодів формування осадового чохла були індивідуальні й неповторні. Вони стали основою для утворення і змін загалом структури південно-західної окраїни Східноєвропейської платформи і, зокрема, Львівсько-Волинського басейну, як частини Львівсько-Люблінського прогину. За інших геоструктурних співвідношень тектонічна будова басейну була би суттєво іншою. У формуванні цієї території, яка зазнала найбільшої активізації у палеозої, в геодинамічному аспекті визначальна роль належить структурним елементам північно-західного і південно-східного простягання. Наукова новизна. На основі аналізу товщини різновікових відкладів регіону показано, що під час геологічного формування басейну на вугленосну товщу різною мірою постійно діяли переважно сили горизонтального стиску. Під їх впливом відбувалось конседиментаційне прогинання території і утворення первинних тектонічних форм, післякарбонових основних тектонічних і морфологічних структур та неодноразових розмивів вугленосних відкладів, які зумовили скорочення розрізу і значне зменшення об'ємів продуктивної частини вугленосної формації. Графічно показано динаміку зміни розташування поверхні кристалічного фундаменту на різних тектонічних етапах формування осадової товщі басейну, нахил якої був неоднаковий. Практична значущість. У результаті проведених досліджень визначено поетапний геодинамічний розвиток території Львівсько-Волинського басейну. В період від початку утворення (зародження) і до розмиву вугленосної формації виділено п'ять етапів її формування, які характеризують особливості вуглеутворення і геодинамічнх процесів. Складена геологічна карта домезозойських відкладів карбонової вугленосної мегаформації Львівсько-Люблінського басейну з важливими тектонічними структурами відображає подібні й відмінні риси геологічної будови Львівсько-Волинського і Люблінського басейнів. Отримані результати сприяють пізнанню загальних процесів формування карбонової вугленосної формації Львівсько-Волинського басейну, а встановлена послідовність уточнює і розширює уявлення про вугленосність, особливості будови вугленосної товщі, морфологію вугільних пластів і має значення для порівняння з вугленосними формаціями інших кам'яновугільних басейнів.

Ключові слова: розломи; кристалічний фундамент; карбон; тектонічні рухи; етапи геодинамічного розвитку, палеозойський прогин; Львівсько-Волинський кам'яновугільний басейн.

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