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https://doi.org/10.23939/jgd2023.02.106

EARTH CRUST OF EASTERN SEGMENT OF UKRAINIAN CARPATHIANS IN THE REGIONAL PROFILE RP-5 ZONE: STRUCTURE, GEODYNAMICS, OIL AND GAS BEARING

The purpose of this work is to analyze and introduce extensively to the scientific community the structure and oil and gas deposits of the Bukovyna lithosphere. This will be based on the unique data gathered from the regional RWM-CDP profile RP-5 and the neighboring regional profiles, in addition to other geological and geophysical data.. The methodology includes a detailed comprehensive analysis of the deep structure and oil and gas bearing and oil and gas prospects of the region and its separate zones based on seismic data on the regional profile RP-5 and nearby oil and gas bearing and oil and gas prospective areas with the involvement of a complex of geological and geophysical data. Results. In the zone of the profile RP-5, the occurrence of sedimentary strata and covers of the Folded Carpathians, the Carpathian foredeep and the edge of East-European craton in the earth's crust of Bukovyna was traced in detail, including the different depth tiers of the Carpathian thrusts and folds. The stepwise dipping of the edge of the East-European craton below the Carpathians is revealed here (generally similar to other segments of the Ukrainian Carpathians). The presence of weakly dislocated autochthonous layers of Mesozoic rocks under the Carpathian thrusts is also established. In these horizons, several bands of folds of the Carpathian extension were discovered. Some of them, in particular, the Lopushna fold, are associated with discovered oil and gas deposits. The study revealed the thickening of the lower crust horizons under the axial part of the Bukovyna Folded Carpathians. In the pre-Carpathian part of the profile, there are 2 deepped ancient “seismofocal” zones of different age of formation and different vergence (researched in detail by S. G. Slonytska using special methods), as well as a number of apophysis-like intrusions. As a result of the comprehensive analysis, the influence of the characteristic features of the local Alpine geodynamic process was traced – the Alpine/Carpathian compression of the lithosphere in the northeast direction orthogonal to the Carpathians and the corresponding thrusts of the allochthon on the previously stepwise dipped here in the southwest direction western edge of the East-European craton as a result of rift-like pre-alpine geodynamic processes. Originality. The peculiarities of the deep structure, geodynamics, seismicity and oil and gas bearing of the Bukovyna lithosphere were determined based on the data of the regional profile RP-5. The research considered new data from oil and gas exploration studies in the subregion and data on various components of the geodynamic process in the whole Carpathian region of Ukraine. The study predicted and confirmed oil and gas prospects of a number of deep folds of autochthonous Mesozoic rocks in the subthrust of the Pokuttya-Bukovyna Carpathians. Practical significance. The research results make it possible to more clearly justify the directions of oil and gas exploration in the subregion.

Key words: Ukrainian Carpathians; Bukovyna; regional profile RP-5; tectonics; geology; geodynamics; oil and gas bearing.

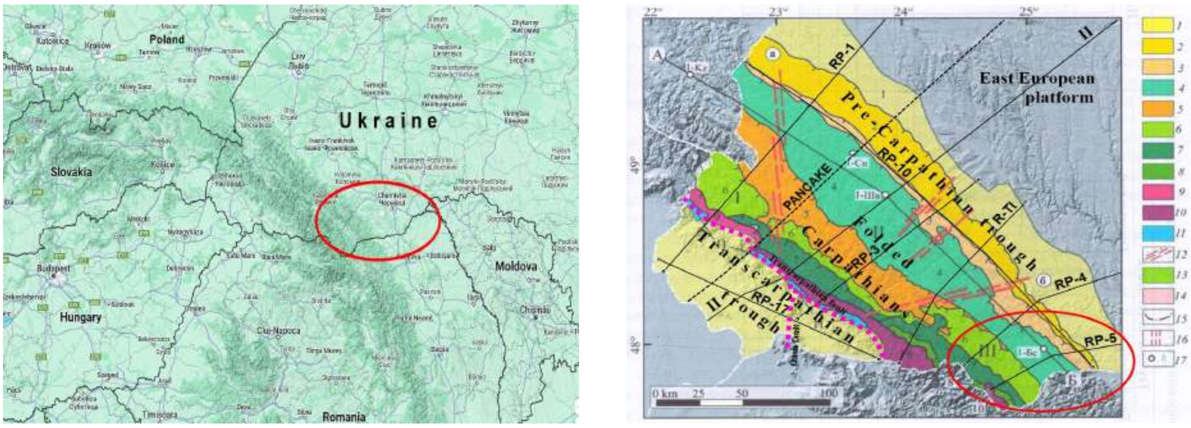
Introduction

The Pokuttia-Bukovyna Carpathians are the eastern part of the Carpathian region of Ukraine (Fig. 1). There are characteristic features of the structure, geodynamics, and seismotectonic process, common to the entire region ([Hofshtein, 1964, 1996; Structure..., 1978; Shpak et al., 1979; Kruglov et al., 1985; Lithosphere... , 1987-93; Atlas…, 1998; Boyko et al., 2003; Pavlyuk, Medvedev, 2004; Starostenko, 2005; Krupskyy 2001, 2020; Gordienko et al., 2011; Hnylko, 2011, 2012; Zayats, 2013; Kurovets et al., 2014; Shlapinskyy, 2015; Murovska et al., 2019; Kravchuk 2021; Amashukeli, 2021, Sandulescu, 1988, 1994; Huismans et al., 1997; Ciulavu et al., 2000, Hippolyte, 2002; Csontos, Vörös, 2004; Seghedi et al., 2004; Grad et al., 2006; Krézsek, Bally, 2006; The Carpathian-Pannonian..., 2006; Schmid et al., 2008; Matenco et al., 2010; Starostenko et al. ., 2013, 2020; Kováčiková et al., 2016; Kiss, 2017; Nakapelyukh et al., 2018; Bielik et al., 2018; Nazarevych et al., 2022] and others), as well as their specific features [Pylypchuk et al., 1985; Sheremeta, 1999; Sheremeta et al., 2004; Shlapinskyy, 2015, 2018; Starostenko et al., 2020], which are traced on the results of a complex analysis of geological-geophysical, geomorphological, seismological and other data [Sheremeta et al., 2002, 2003, 2004, 2011, 2019; Nazarevych A. et al., 2005; Nazarevych L., 2006; Nazarevych L., Nazarevych A., 2007; Nazarevych A., Nazarevych L., 2007; Sheremeta et al., 2001].

As to the geomorphological characteristics of the subregion [Kravchuk, 2021], here begins the turn of the Carpathian ridges from a diagonal northwest-southeast direction (azimuth ~130º) to a more submeridional (azimuth ~150-170º) direction (Fig. 1, *a*). This is closely related to the deep structure, paleo- and modern geodynamics of this territory and its surroundings ([Structure..., 1978; Kruglov et al., 1985; Lithosphere..., 1987–1993; Tectonic..., 1994; Krupsky, 2001; Boyko et al., 2003; Starostenko, 2005; Hnylko, 2011; Gordienko et al., 2011; Sandulescu, 1988, 1994; Csontos, Vörös, 2004; The Carpathian-Pannonian..., 2006; Kiss, 2017] and oth.). Recently obtained new geological and geophysical data make it possible to more clearly define the features of the deep structure of the lithosphere of the subregion, its geodynamics and oil and gas prospects [Lebid` et al., 2009; Lozynyak et al., 2011; Shlapinskyy, 2015; Modern..., 2015; Slonytska, 2017; Murovska et al., 2019; Starostenko et al., 2020; Amashukeli, 2021]. However, the basic ones here are the unique detailed data on the regional profile RP-5 (m. Chyvchyn – v. Dynovtsi) [Sheremeta, 1999; Hnievush, Yaremin, 1998] and the results of research in the area of the Lopushna oil field [Shpak et al., 1979; Sheremeta et al., 2004].

Purpose

The purpose of this work is to analyze and introduce extensively to the scientific community the structure and oil and gas deposits of the Bukovyna lithosphere (the eastern part of the Carpathian region of Ukraine, Fig. 1). This will be based on the unique data gathered from the regional RWM-CDP profile RP-5 (Figs. 3–6) and the neighboring regional profiles, in addition to other geological and geophysical data. It should be noted that although the RP-5 profile was worked out in 1993–1994 by the seismic exploration party No. 5393 of WUGPE using advanced methods at that time [Sheremeta, 1999; Hnievush, Yaremin, 1998] (see below). Further data was also processed on computers using advanced methods [Sheremeta et al., 2004]. The constructions presented in the article were made in 1995–1998 and published in 1999 [Sheremeta, 1999] (Fig. 2). These data for a number of reasons did not become available to the wider scientific community. Therefore, this publication is designed to fill this gap.



a b

Fig. 1. The Bukovyna subregion (marked with an red oval) on the map of Central Europe (map base Google Maps) (a) and on the map of the general tectonic zoning of the Ukrainian Carpathians (b) (map according to [Shlapinskyy, 2015; Krupskyy, 2020], regional profiles are shown).

Methodology and data

The methodology of our research includes a detailed comprehensive analysis of the deep structure, geodynamics and oil and gas bearing and oil and gas prospects of the region and its separate zones based on seismic data on the regional profile RP-5 and nearby oil and gas bearing and oil and gas prospective areas with the involvement of a complex of geological and geophysical data [Shpak et al., 1979; Pylypchuk et al., 1985; Sheremeta, 1999; Sheremeat et al., 2004; Borsuk, Gnevush, 2002; Cheban, Lyashchuk, 2007].

The research uses data from our earlier seismotectonic studies [Nazarevych A., Nazarevych L., 2002; Nazarevych A. et al., 2005; Nazarevych L., 2006; Nazarevych L., Nazarevych A., 2007, 2012, 2018; Nazarevych, Starodub, 2010; Kováčiková et al., 2016]. We also utilize other geological and geophysical data [Ladanivskyy et al., 2005; Lebyd` et al., 2009; Shlapinskyy, 2015; Slonytska, 2017; Kiss, 2017; Starostenko et al., 2020], taking into account the results of the geomorphological analysis of the structure and genesis of the relief of the territory

[Bayrak, 2006; Kravchuk, 2021]. Additionally, the study processes geodetic data on the modern geodynamics of the Carpathian region of Ukraine and the results of their complex interpretation [Somov, 1990; Starostenko, 2005; Modern..., 2015; Nazarevych A. et al., 2022, 2023].

A general comparison of the data on the RP-5 profile with the data on the developed much later (2014), located nearby (20–35 km to the east) profile DSZ-RWCM RomUkrSeis [Starostenko et al., 2020; Amashukeli, 2021] was carried out.

The methodology of seismic research on the RP-5 profile and in the neighboring areas of Bukovyna combined the most advanced methodological developments at that time (the 1980–1990) both in fieldwork and in computer data processing [Sheremeta et al., 2004, Borsuk, Gnevush, 2002].

Systematic seismic survey work on the territory of Bukovyna began in 1969 [Sheremeta et al., 2004]. Since 1977, for the first time in the world practice of seismic research on the territory of the Pokuttya-Bukovyna Carpathians seismic work on the RP-5 profile began to be conducted on the basis of the recommendation of P. M. Sheremeta by the wide profile method – the method of longitudinal-non-longitudinal profiling of the CDPM (common depth point method) with simultaneous carrying out of three or four profiles, the distance between which was 1.5–2 km. This made it possible to take into account the impact of reflections from structural elements of the appropriate structural scale, lateral relative to the main profile, due to quasi-3D constructions, and significantly improve the final quality of the results of seismic surveys.

The recording of seismic data was carried out at times up to 6–9 s after the excitation of the waves, which made it possible to trace in detail the structure of the upper (from 12–18 to 15–25 km, depending on the velocity structure of different horizons of the crust [Sheremeta et al., 2004, Borsuk, Gnevush, 2002]). At some pickets, the recording was carried out at times up to 12–15–18 s, which made it possible to trace in general the occurrence and extension of a number of deeper reflective boundaries up to the Moho boundary. Work on the areas was carried out using the system of cross profiles, this is practically close to modern quasi-3D seismic.

Structural constructions were carried out based on the most modern at that time specially developed software packages for seismic data processing, in particular, SPS-PC (author M.O. Golyarchuk) with the use of amplitude restoration procedures, spatial filtering, deconvolution, band filtering, velocity analysis, adjustment and using static corrections, migration, etc. [Borsuk, Gnevush, 2002]. Special mathematical modeling was also carried out using matrix and finite element methods and iterative procedures for calculating velocity models with successive approximation and refinement of their geometric and velocity parameters and using calculated (synthetic) seismograms built on the basis of AL data and core studies of wells in the profile zone (Yu. P. Starodub, T. B. Brych, KB IGPh NAS of Ukraine, specialists of the Technological Center of the SGC “Ukrgeophysics” (Kyiv) and others), processing was carried out on large computers, in particular, on EC 1061, as well as on PC.

For the transition from temporal to depth sections, the lateral and depth features of the velocity characteristics of the crustal horizons were studied and taken into account according to borehole and other geological and geophysical data [Sheremeta et al., 2004] (see also below, the subsection on oil and gas potential and the Lopushnyan field). At the structural constructions, expanded velocity graphs were used on seismic profiles. For this, maps of the dependence of the depth on the double time $H=f(2t)$ were constructed with time steps of 0.2 seconds (0.2; 0.4;...2.2) from the reference line plus 600 m. This gave, in particular, the ability to link seismic profiles with well sections, correctly construct the volume-spatial configuration of various-scale geological structures, reliably trace their depth-spatial extension, predict oil and gas prospective structures, trace the occurrence of discovered oil and gas deposits and establish the optimal mode of their exploitation [Atlas, 1998; Sheremeta, 1999; Sheremeta et al., 2001; 2004].

The interpretation of the data in the future also took into account computer modeling of the features of the lithosphere deep structure of the subregion based on data on geophysical fields [Sheremeta et al., 2019]. These are, in particular, the works of S. G. Slonytska on complex modeling of features of the lithosphere deep structure based on geomagnetic and gravity data [Slonytska, 2017], works of V. I. Tregubenko on MTS [Tregubenko et al., 1994, Lebid` et al., 2009] and others.

The geological interpretation and construction of the seismo-geological profile, as well as the further analysis of the data of deep geophysical and geological-tectonic and surface and borehole geological studies were involved (authors – V. V. Glushko, S. S. Kruglov, P. Yu. Lozynyak, M. Y. Petrashkevych, V. V. Kuzovenko, V. E. Shlapinskyy, Y. Z. Krupskyy and others, see in particular, [Atlas..., 1998; Pylypchuk et al., 1984; Kruglov et al., 1985; Lithosphere..., 1987–1993; Osadchyy et al., 1999; Garasymchuk, 2001; Boyko et al., 2003; Starostenko, 2005; Monchak et al., 2010; Hnylko, 2011, 2012; Gordienko et al., 2011; Prokopiv, Hrytsyshyn, 2012; Zayats, 2013; Khomyak L., Khomyak M., 2013; Kurovets et al., 2014; Shlapinskyy, 2015, 2018; Krupskyy, 2001, 2020; Starostenko et al. al., 2013, 2020; The Carpathian-Pannonian..., 2006]).

The Romanian part of the profile (section: town Breaza (Romania) – Mount Ciblesu – Mount Plak – town Vysheul-de-Sous – Mount Chyvchyn (Ukraine) was constructed according to the data of the Romanian geologists G. Kreitner, M. Sandulescu, N. Oncescu and others [Oncescu, 1960; Sandulescu, 1988, 1994]. The data of geological-tectonic and geodynamic constructions of many foreign authors regarding the territory of Romania and the entire mega-region of Pancardia were also included in the comprehensive analysis [Ciulavu et al., 2000; Hippolyte, 2002; Seghedi et al. al., 2004; Grad et al., 2006; Krézsek, Bally, 2006; Schmid et al., 2008; Kiss, 2017; Bielik et al., 2018; Nakapelyukh et al., 2018].

Results

The general structure of the Bukovyna lithosphere according to data on the profile RP-5

Geographically, Bukovyna is the easternmost part of the Carpathian region of Ukraine (Fig. 1, *a*). The subregion is located on the Ukrainian-Romanian borderland, between the middle flow of the Dniester River and the main Carpathian range, in the valleys of the upper flow of the Prut and Syret rivers, covering all the Bukovyna Carpathians and Pre-Carpathians, the Suchava plateau and the Khotyn highlands (between the valleys of the Prut and Dniester Rivers). Morphologically, Bukovyna covers the eastern segment of the northeastern megaslope of the Ukrainian Carpathians (near the border with Romania) and the Pre-Carpathian highlands (near the border with Moldova). In relief, it is from the watershed, the highest in the Ukrainian Carpathians, the Verkhovyna ridge (height up to over 2000 m) and the Chyvch mountains on the border with Romania (height over 1500 m, in particular, Mount Chyvchyn with a height of 1766 m) and the Yavirnyk (height over 1500 m) and Hrynyava (height up to more than 1300 m) ridges, as well as a number of other ridges of the mid-mountains of the same height (up to 1.300 m) of the Carpathian extension in the Shepit – Verkhovyna strip and further to the northeast a number of ridges of the Verkhovyna-Putyla low mountains (height up to over 800–1000–1200 m), so-called Bukovynska Polonyna. Further to the northeast (in the area of town Krasnoilsk) the mountainous terrain is interchanged on the highlands of the Suchava plateau, which is quite fragmented by river valleys (the Syret River and its tributaries) (apical surfaces at absolute heights of up to 450–500 m, river valleys at absolute heights 300–350 m), and behind the valley of the Prut River is interchanged on the Khotyn plateau with an also rather fragmented relief.

Tectonically, the territory of Bukovyna covers the eastern parts (eastern segment) of the structural units of the Ukrainian Folded Carpathians (Fig. 1, *b*, Fig. 2), the so-called Hutsulskyy megablock (after V. V. Hlushko [Kruglov et al., 1985]), the border between which (according to the determination of V. E. Shlapinsky [Shlapinskyy, 2015, 2018]) passes along the Hutsulskyy (Pokutskyy) fault (approximately along the line v. Sloboda Rungurska – v. Yasinya). From the southwest to the northeast, it is from the northeastern edges of the Marmarosh crystalline massif through the Carpathian nappes of fold-thrust structure to the structures of the Carpathian foredeep and the edge (Podillya-Bukovyna uplift) of the East-European craton.

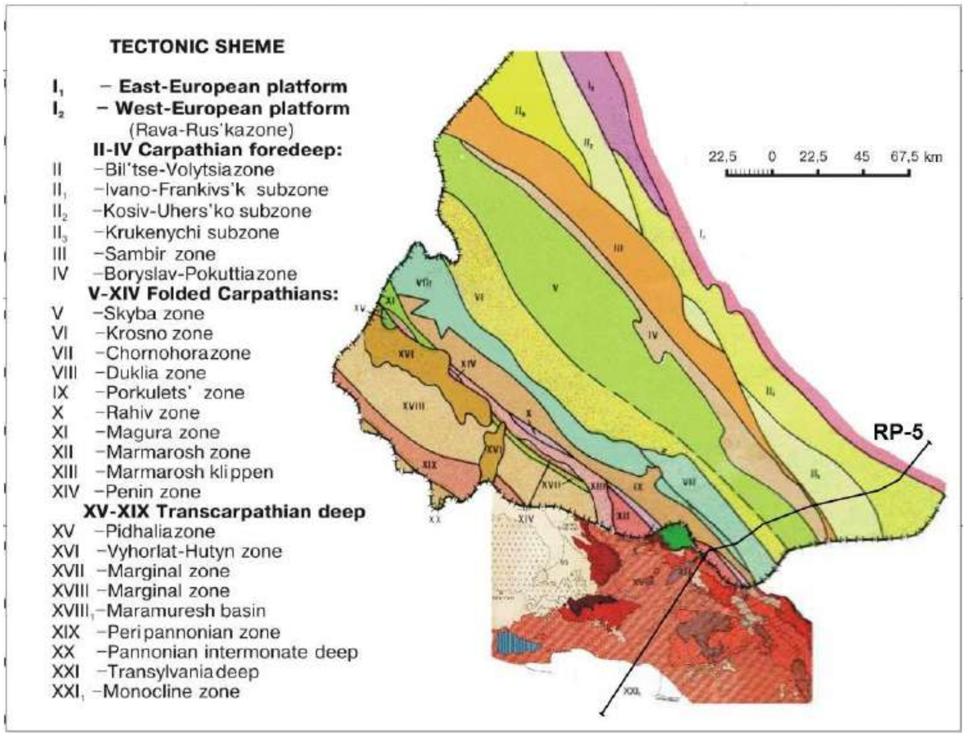
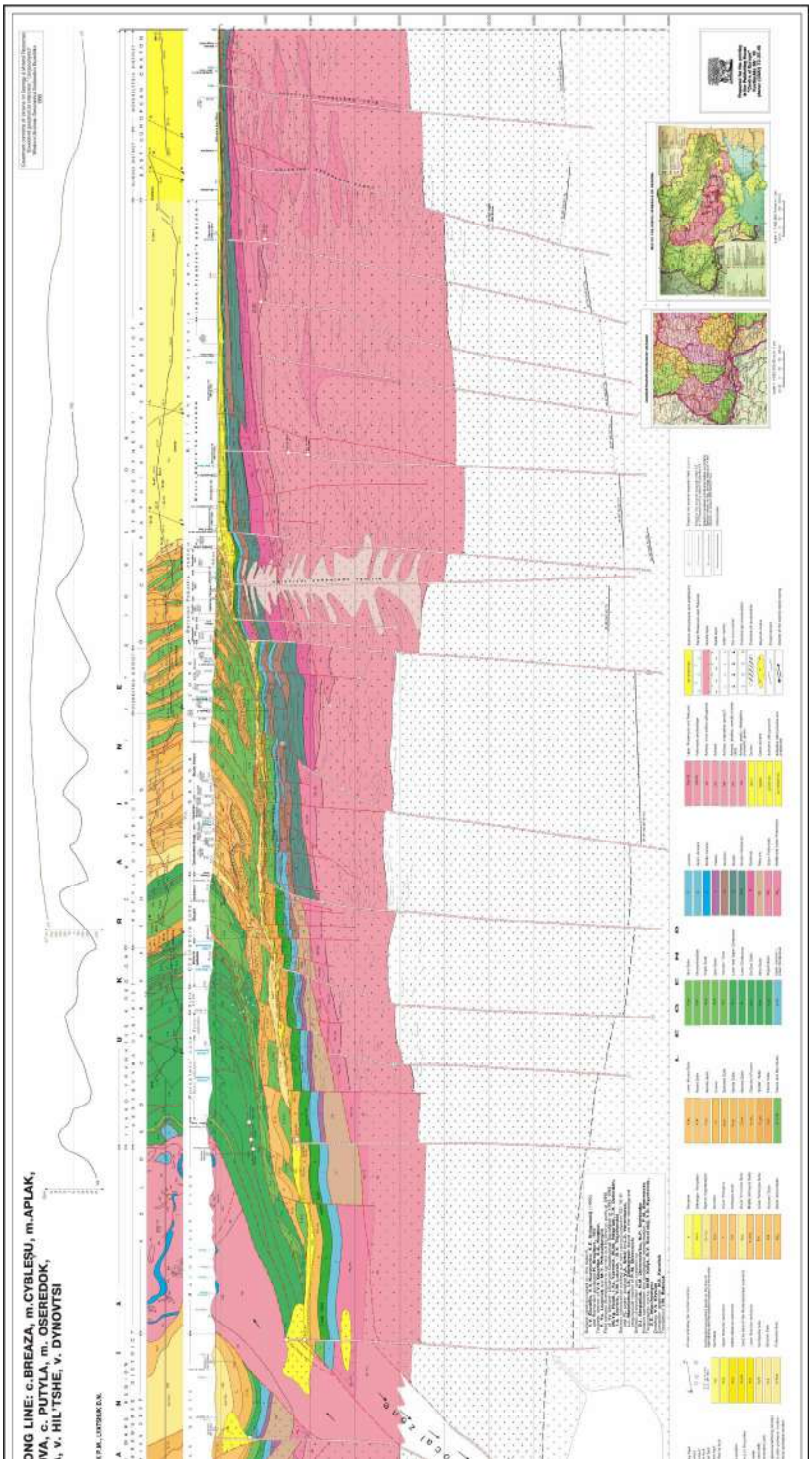
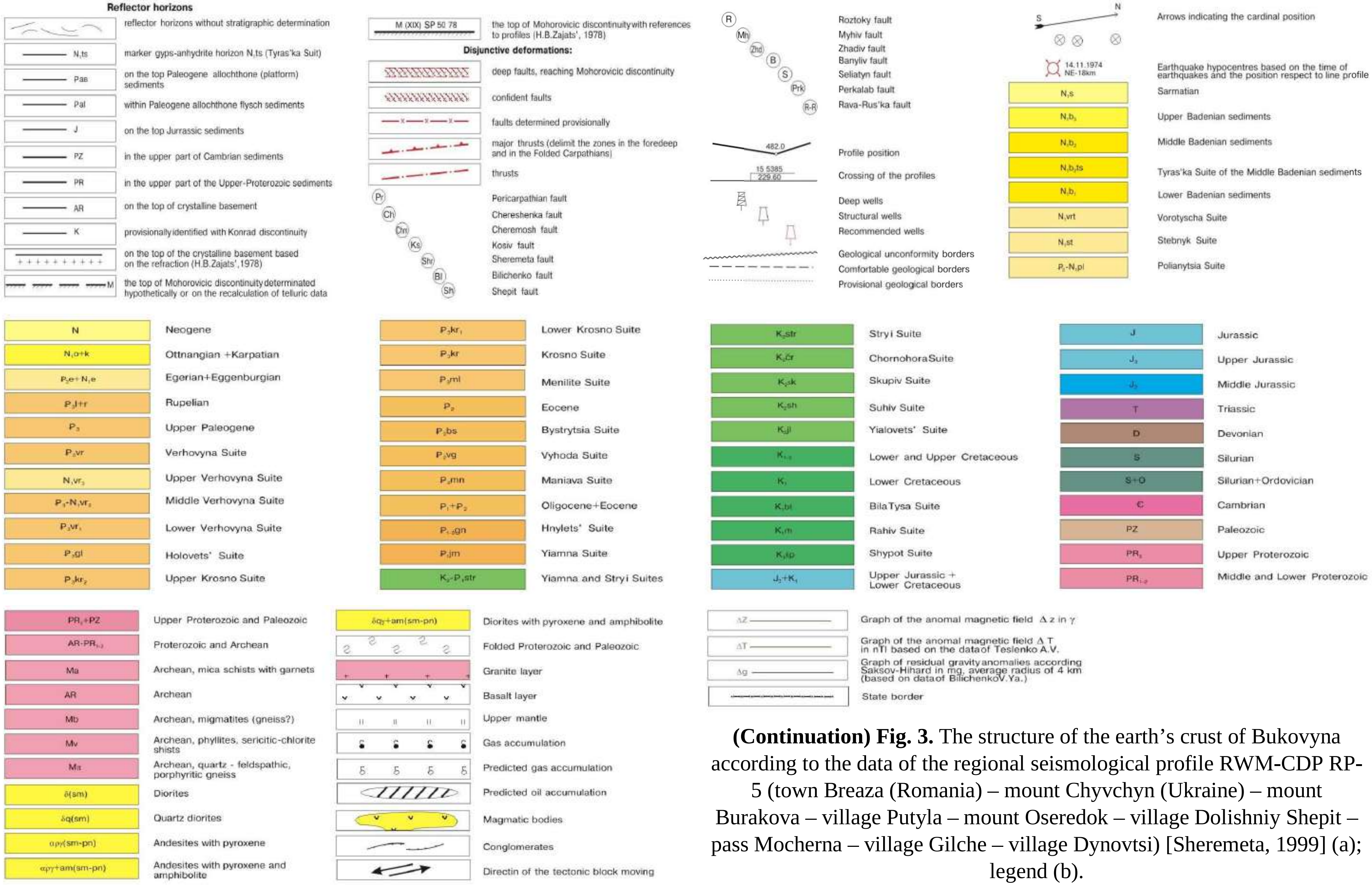


Fig. 2. Localization of the profile RP-5 on the detailed tectonic zoning map of Ukrainian Carpathians and adjacent areas of Romania [Sheremeta, 1999].



a

Fig. 3. The structure of the earth's crust of Bukovyna according to the data of the regional seismological profile RWM-CDP RP-5 (town Breaza (Romania) – mount Chyvchyn (Ukraine) – mount Burakova – village Putyla – mount Oseredok – village Dolishniy Shepit – pass Mocherna – village Gilche – village Dynovtsi) [Sheremeta, 1999] (a); legend (b).



(Continuation) Fig. 3. The structure of the earth's crust of Bukovyna according to the data of the regional seismological profile RWM-CDP RP-5 (town Breaza (Romania) – mount Chyvchyn (Ukraine) – mount Burakova – village Putyla – mount Oseredok – village Dolishniy Shepit – pass Mocherna – village Gilche – village Dynovtsi) [Sheremeta, 1999] (a); legend (b).

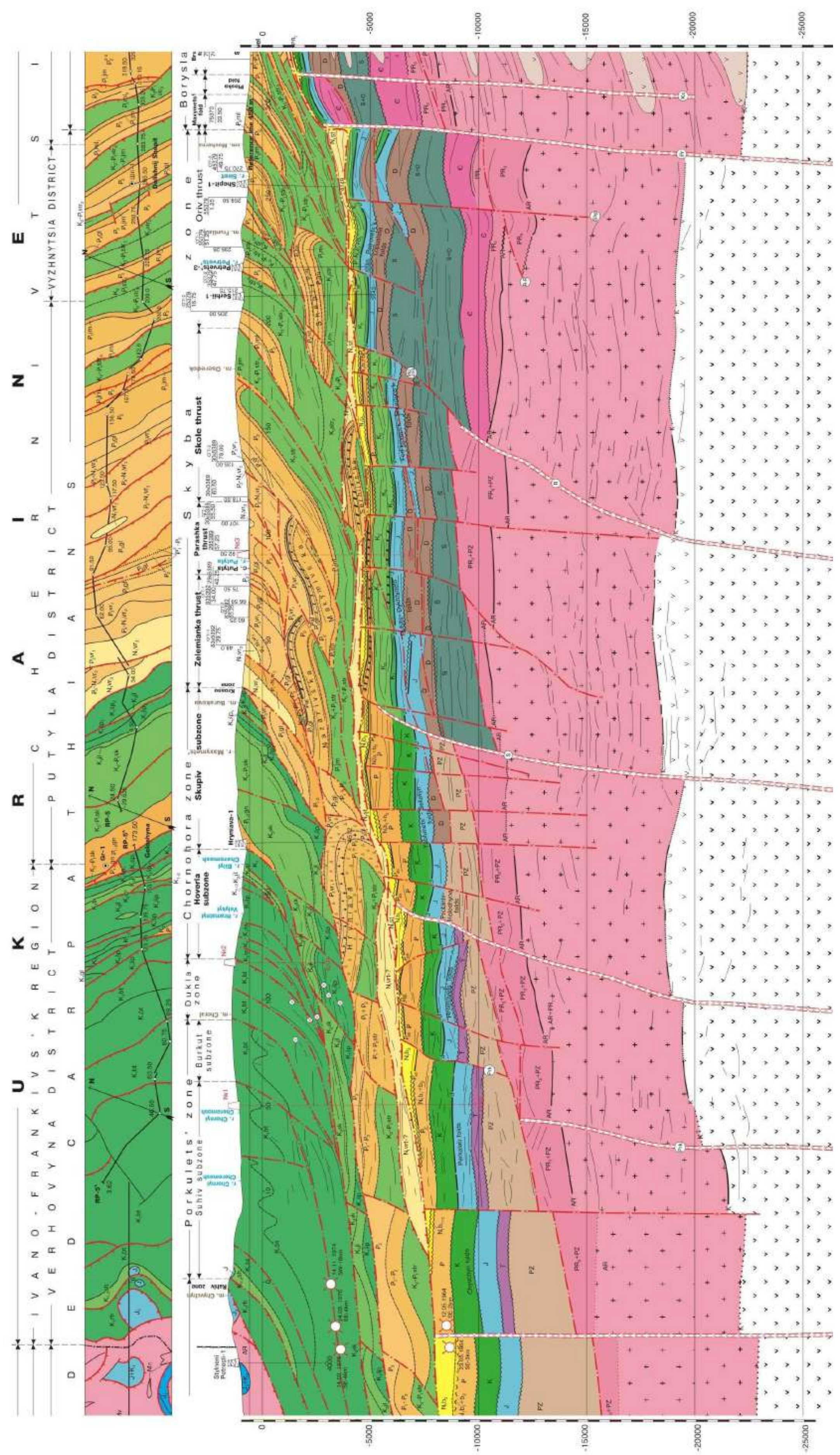


Fig. 4. Detailed structure of the upper (at depths of 0–25 km) horizons of the earth's crust of Bukovyna according to data from the profile RP-5 (central part – Pokuttya-Bukovyna Carpathians) [Sheremeta, 1999]. Conventional notations see in Fig. 3, *b*.

The deep structure of the lithosphere of Pokuttya, Bukovyna and the adjacent part of Romania was studied in detail by regional RWM-CDP profiles RP-5 (town Breaza (Romania) – Mount Chyvchyn – village Putyla – village Dolishnyy Shepit – village Dynovtsi) (Fig. 3–6) [Sheremeta, 1999; Hnievush, Yaremin, 1998], RP-4a (town Kosiv – town Melnytsia Podilska), RP-10 (Kolomyya city – village Mezhyrichchya) [Hnievush, Yaremin, 1998] and the newest cross-border profile RomUkrSeis [Starostenko et al., 2020].

Analyzing the structure of the earth's crust of Bukovyna according to the data of the profile RP-5 (Figs. 3–6), we note the following. In general, here, as in all the Ukrainian Carpathians, a system of large thrusts and folds of northeastern vergence can be traced in the allochthonous part. The main thrust plane of the Carpathian nappes in the south-western near-romanian part of the Pokuttya-Bukovyna Carpathians (the area of the mount Chyvchyn) is localized at a depth of about 8 km, rising smoothly in the direction of the Pericarpathian fault (Pericarpathian in Figs. 3–6) to a depth of 4 km, and then quite sharply (at a distance of 10 km, in within the limits of the Boryslav-Pokuttya zone of foredeep) rises upwards. This plane is reliably controlled by deep wells (Rozhen-1, 6175 m, Sergiyi-1, 5642 m, Petrovets-3, 5585 m, Shepit-1, 4145 m, Solonets-2 and others). This thrust plane is underlain by the sediments of the Carpathian foreland, which extend far to the southwest under the Carpathians, to the zone of a sharp decrease of the thickness of the earth's crust and is traced over almost the entire territory of the subregion on the reflective horizon J (roof of the Jurassic), for which detailed structural constructions were made here (see further, Fig. 8).

We can see that the Pre-Carpathian fault with an amplitude of about 3 km divides the foreland into 2 parts: the uplifted northeastern one (structures of the Carpathian foredeep and the edge of the platform, the Mesozoic is at a depth of 0.3–3.0 km) and the lowered southwestern (subcarpathian), where the Mesozoic is in the subthrust, at depths of 4–15 km.

Autochthonous sediments are represented by Proterozoic, Paleozoic, Mesozoic and Cenozoic rocks. The autochthon on the system of stepped faults of the Carpathian extension sinks in the southwest direction to a depth of 10–15 km. It is also dissected by transverse fault-slips, which, in interaction with lengthwise ones, determined the block style of the tectonics of the Carpathians' bed. Amplitudes of vertical displacements on lengthwise faults are up to 2-3 km, and on transverse ones do not exceed 300 m. Transverse faults-slips are younger and, as indicated by seismological data (see below), they are still active to this day, along with lengthwise ones.

The allochthon (Figs. 3–5) is represented by a multi-tiered system of the Carpathian thrusts and folds of the Porkulets, Dukla, Chornohora, and Skyba zones of the Folded Carpathians and the Boryslav-Pokuttia zone of the Carpathian foredeep (see below for details).

The Conrad boundary is located in the profile at depths of 13–17 km under the Carpathians (forming here an anticlinal uplift with a peak in the area of town Putyla) and at depths of 20–22 km under the Carpathian foredeep. The Moho surface, on the contrary, forms a depression under the Carpathians, dipping from 36–37 and 39–41 km (Breasa (Romania) and Chyvchyn (Ukraine)) to 47 km in the Putyla – Shepit zone (under the outer edge of the Carpathian thrusts) and rising again up to 38–40 km in the direction of the platform.

As to the localization of the Teisseire-Tornquist zone in this area, according to our conclusions, it lies in the zone between the Seliatyn, Roztoky and Pericarpathian faults (judging by the presence here and the structure of Silurian and Ordovician sediments in the Carpathian subthrust), although then its initial graben-rift structure (especially on the southwestern side) was noticeably disturbed due to the effect of alpine/carpathian compression on the lower and middle crust of the subregion and the formation here of northeast-inclined faults of the Carpathian extension and certain thrust structures (“cornices”) of the same vergence at depths 5–15 km, in the horizons of the Paleo-Mesozoic bed of the Carpathians.

Comparing the deep structure of studied by us the eastern Pokuttia-Bukovyna segment of the Ukrainian Carpathians (Hutsulskyy megablock of the Carpathians, after V. Shlapinskyy [Shlapinskyy, 2015, 2018]) with the structure of the neighboring central segment (Boykivskyy megablock), located to the north-west, we note that in the general the structures of the basement (bed) of the Carpathians in Bukovyna are significantly raised, that is noted by many authors based on various geological and geophysical data, in particular, seismic and gravity field ([Shlapinskyy, 2015, 2018, Kiss, 2017] and others).

The structure of the upper crustal horizons of the subregion according to data on the profile RP-5

The structure of the upper horizons of the Bukovyna crust according to the profile RP-5 is shown in detail in Fig. 4–6. To that we note that in the legend to the profile (Fig. 3, *b*) all the layers and strata of rocks, available in the section, are presented in detail with their names and geochronology.

The Carpathian thrusts on the territory of Bukovyna (Fig. 4) have a complex multi-tiered structure. On the section from the Romanian border (Mount Chyvchyn) to the village Holoshyna profile RP-5 crosses the system of thrusts of the upper tier (of relatively uncomplicated structure) of the Porkulets (Suhiv and Burkut subzones), Dukla and partially Chornohora (Hoverla subzone) zones. The sole of these thrusts smoothly rises from the abs. depth of 5 km in the area of Mount Chyvchyn to 1.5 km in the zone of crossing of the valley of the Bilyi Cheremosh River, where it sharply wedges upwards (at a distance of up to 2 km). Under these thrusts, horizons of rocks of the middle tier, Skupiv subzone of the Chornohora zone, broken into blocks by the carpathian and transverse faults and complicated by folds, are traced, with a thickness of about 1 km in the section from the Mount Chyvchyn (abs. depth of 4–5 km) to the Mount Choral (abs. depth 2.5–4 km), with a thickening of up to 1.5–2 km in the segment to the crossing the profile of the Bilyi Cheremosh River valley, and up to 3–4 km further to the northeast, in the area where these rocks come to the surface. Below, in the depth interval of 6–8 km, on this section of the profile the structures of the lower layer of thrusts are traced, the buried horizons of the Skyba zone of the Folded Carpathians (1.5–2.5 km thick) with generally similar structural features. But in the area of the Bilyi Cheremosh River valley, these horizons thicken up to 3 km (abs. depth 2.5–5.5 km) and form an upturned Hrynyava fold, exposed in the upper frontal part by the well Hrynyava-1 (depth 4612 m).

Another feature of the allochthon section along this profile is the presence of a thin (mainly 0.5 km thick, with thickening in some places up to 0.8–1 km) horizon at its bottom, associated with Neogene strata of the Sambir zone of the Carpathian foredeep. This layer originates northeast of Mount Chyvchyn (abs. depth of 7.5–8 km) and rises to abs. depth of 5.5 km (in the area of the Bilyi Cheremosh River valley).

To the north-east of the Hrynyava fold, the bottom of the Carpathian thrusts (the roof of the autochthon) undergoes a noticeable uplift (from an absolute depth of 5.5 km to 4 km) within the southern part (on a section of 3–4 km) of the lengthwise block, broken by small near Carpathian ruptures between the Sheremeta and Seliatyn faults, forming here one of the pronounced steps of such uplift. This is related to the thickening of the relatively somewhat ductile lower crust here under the influence of Alpine/Carpathian compression.

As for the upper Carpathian thrusts, in this part of the profile, from village Holoshyna (crossing of the valley of the Bilyi Cheremosh River) to the Mount Burakova, from a depth of about 3 km to the surface (on a section of 6–7 km), thrust rocks of the Skupiv subzone of the Chornohora zone of the Carpathians lie in a thick wedge. Further, to the town Putyla and even further, to the Mount Oseredok, at shallow depths (from an abs. depth of 4.5 km to the surface) the structure of the Carpathians is formed here by thrusts of the Skyba zone (Zelemianka, Parashka and Skole thrusts). The first 2 of them are on abs. depths of 1–2 km. They are complicated by the lower layer of folds, Nazarivs’ka and Maxymivs’ka, which are underlain by layers of rocks of the Skole skyba (at abs. depths of 2–3.5 km). Under the frontal part of the Skole skyba in the zone of the bottom of the thrusts (abs. depth of 3.5–4.5 km) the Serhiivs’ka fold is traced. Further to the northeast, from the northern slopes of mount Oseredok to the Mocherna pass (zone of the Pericarpathian fault) at near-surface depths and on the surface, there are rocks of Oriv thrusts, in which at depths of 2–2.8 km the Shepit fold is traced, traversed by the Serhii-1 and Petrovets’-3 wells.

To the northeast of the Mocherna pass, the profile RP-5 crosses the structures of the Boryslav-Pokuttia zone of the Carpathian foredeep (shown in detail in Fig. 5). These are the Maxymets, Brusnyi, Hil`che and Karmatura folds. The roof of these thrusts’ dips to the southwest at a distance of up to 6 km to a depth of 1.3–1.8 km. The bottom of these thrust-folds on the roof of the rocks of the Sambir zone rises smoothly in the same area to the north-east from a depth of about 3.8 km to a depth of about 3–2.8 km in the zone of the Pericarpathian fault and further rises sharply at a distance of 2 km (in the section between it and the Kosiv fault) to 1.5 km, even further it become near-horizontal (climbing for the next 6 km (in the area of the village Hil`che) to 0.5 km deep).

The structure of the upper horizons of the crust on the profile RP-5 in the area of the Carpathian foredeep and the edge of the East-European craton (in the section northeast from the village Gilche to the village Dynovtsi) is much simpler (Fig. 6). Here, layers of Neogene sedimentary rocks with a thickness ranging from 1 km in the area of Banyliv-Pidhirnyi to 300 m in the area of the village Hrushivka lie in a thin wedge on the rocks of the basement, further northeast to the village Lukvytsa those rocks are wedged out to abt. 100–150 m. Only in the area of Banyliv-Pidhirnyi, southwest of the Chereshenka fault (between it and the structures of the Sambir zone), in a section about 2.5 km long, the total thickness of these deposits reaches 2 km thanks to the lowered here pre-Neogene basement.

As for the relations of the geological structures of the upper horizons of the crust of the Pokuttya-Bukovyna Carpathians on the territory of Ukraine and in the adjacent areas of Romania, these issues are considered in detail in the works of V.E. Shlapinskyy [Shlapinskyy, 2015, 2018].

Regarding the structure of the autochthon of the Carpathians along the profile RP-5 (see Fig. 4), we once again note its gradual immersion under the Carpathians and fragmentation into small blocks by numerous subvertical faults (see also below, Figs. 8 and 9), some of which are shallow and can be traced only to 5–7 km deep into the basement, and others, deeper, go all the way to the mantle. In the subthrust part, in the zone of the roof of the autochthon, a number of relatively weakly dislocated horizons, identified by their seismic and other characteristics as Paleogene, Cretaceous, and Jurassic, have been traced by seismic survey data. These layers with a total thickness of about 4 km gradually rise from the interval of abs. depths of 8–12 km in the area of

Mount Chyvchyn to an interval of 5–8.5 km in the crossing zone of the valley of the Bilyi Cheremosh River. In the periaxial (southwestern) part of the profile (between the subvertical Bilichenko fault and the northeast-tilted Sheremeta fault), below them, a horizon identified as Triassic, and even lower, Paleozoic, Proterozoic, and Archaean horizons are traced.

Further to the northeast, these Mesozoic layers (without the Triassic) lie with a slight rise and somewhat vaulted in the section from the Sheremeta fault (depth interval 6–8.5 km) to the strongly inclined deep Roztoky fault (depth interval 4.5–6.5 km), the fault itself branches here in the direction of the shallow layers into Myhiv and Zhadiv smaller faults. Even further to the northeast, these Mesozoic layers extend in a rather thin (total thickness of 1–1.5 km) and generally close to a subhorizontal stack of layers to the zone of the Pericarpathian fault.

We also pay attention to the fact that in the described above section of the profile RP-5 (Figs. 4 and 5) under the Carpathian Mesozoic between Seliatyn fault in the southwest and Pericarpathian fault in the northeast (from depths of 7.5–11 km in the southwest to depths of 4–9 km in the northeast) the Devonian, Silurian and Ordovician layers are traced, they are absent in the southwest of the section. In our opinion, this may indicate the passage here of the trans-European ancient Tesseire-Tornquist rift-graben zone, the border between the East and West European cratons. The original structure of this zone was obviously significantly disturbed by subsequent (in particular, Alpine/Carpathian) tectonic processes. This is evidenced by the cornice-like overhang of Mesozoic rocks over Paleozoic ones on the former southwestern side of the structure, in the zone of the Seliatin fault, and the overthrust 2-tier structure of Devonian and Silurian in its northeastern zone, between the Rostoky (Myhiv and Zhadiv) and Pericarpathian faults. What’s more, here under the Devonian at depths of 8–11 km, the layer of carbon with a thickness of about 1.5 km has been traced.

In the described Carpathian section of the profile in the Paleogene, Cretaceous and Jurassic horizons, according to the data of seismic survey and gravity survey, up to 10 zones of quite distinct anticlinal folds have been identified (see also below, Figs. 8 and 9): Petrovets’k-Lopushna, Fed’kovets’k-Shurdyns’k, Putyla-Dykhtynets, Yablunets’-Seliatyn, Probiniv-Holoshyna, Gromovets’, Perkalab, Chyvchyn and another two and possibly three zones on the territory of Romania.

In general, we also note that the thickness of these sediments increases in the southwest direction. Thus, if in the first zone of anticlinal structures the thickness of the Paleogene autochthon is about 30 m, then within the third zone (Putyla fold) it reaches 300 m, and within the tenth zone the thickness of Paleogene and Cretaceous sediments already reaches 1500–2000 m. These sediments were not significantly disturbed or engrossed during the formation of the Carpathians and lie autochthonously, obviously, because they were accumulated on a thick and light continental crust, which could not be subducted due to its relatively low density. We should also note that the process of thrusting of the Carpathian covers, despite the significant amplitudes of such thrusting, apparently proceeded in the sliding mode without significant resistance from the Mesozoic strata, as it did not lead to their pronounced scalping.

To this, we note that Mesozoic layers in the foreland of the Carpathians, according to the MTS research data (V. I. Tregubenko [Lebid’ et al., 2009]) are characterized (see Fig. 7) by rather low resistivities (increased conductivity), which is consistent with well data [Pylypchuk et al., 1984; Prokopiv, Hrytsyshyn, 2012] and testifies to their notable porosity and partial hydration, as well as to their potential as oil and gas reservoirs, in particular in trap-type structures within the folds present here. This is also evidenced by hydrogeological data in the area of the Lopushna deposit (see below), in particular, the presence of a zone of AHRP (with a coefficient of 1.84) in the Upper Jurassic horizon and similar zones of AHRP in the selected three other hydrodynamic systems of the autochthon (Cretaceous, Paleogene, and Neogene) ([Osadchyy et al., 1999; Garasymchuk, 2001] and others). Such hydration of these underlying layers could also be one of the important factors for the above-mentioned easily thrusting of the Carpathian covers on them (the so-called “damp sponge” anti-friction effect).

Examining the structure of the subthrust structures of the Bukovyna crust in the zone from the Pericarpathian fault further to the northeast, to the Chereshenka fault (Fig. 5), we see that the Mesozoic (Cretaceous and Jurassic) here lie in a thin (about 700–800 m) stack of layers, subhorizontal (abs. depth of 1.7–2.3 km) step with a deep of up to 3.5 km abs. southeast part and elevated to 1.3 km abs. north-eastern part. Below them on the abs. depths of 1.2–3.8 km, a thick (1.6–2 km thick) stack of Paleozoic rocks (Carboniferous, Ordovician, Silurian, and Devonian) is traced here. A notable feature of these crustal horizons is the presence here of the deep (traced to the very boundary K, depths of 23–25 km) Hil’che apophysiform intrusion, which broke through Archean, Proterozoic, and Paleozoic strata along the Banyliv vertical fault of the carpathian extension. This intrusion, like a number of others reveald further northwest along this fault (see below), is clearly tracked by seismic survey and gravity anomalies [Sheremeta et al., 2011, 2019].

Further to the northeast of the Chereshenka fault, Paleozoic rocks (Carboniferous, Ordovician, Silurian, and Devonian) lie close to the surface (abs. depth 0.6–1.9 km) and relatively smoothly, in subhorizontal layers, the thickness of which decreases from 1.4 km in the Storozhynets area up to 0.9 km in the Tysovets – Hrushivka area and up to 0.4 km in the Lukvytsya – Prypruttya area (here the absolute depth of the Paleozoic deposits is 0–0.8 km). A small thrust (horizontal amplitude of 1–1.5 km and vertical displacement in Carboniferous, Silurian and Devonian order of 0.7 km) is observed northeast of the Storozhynets` fault.

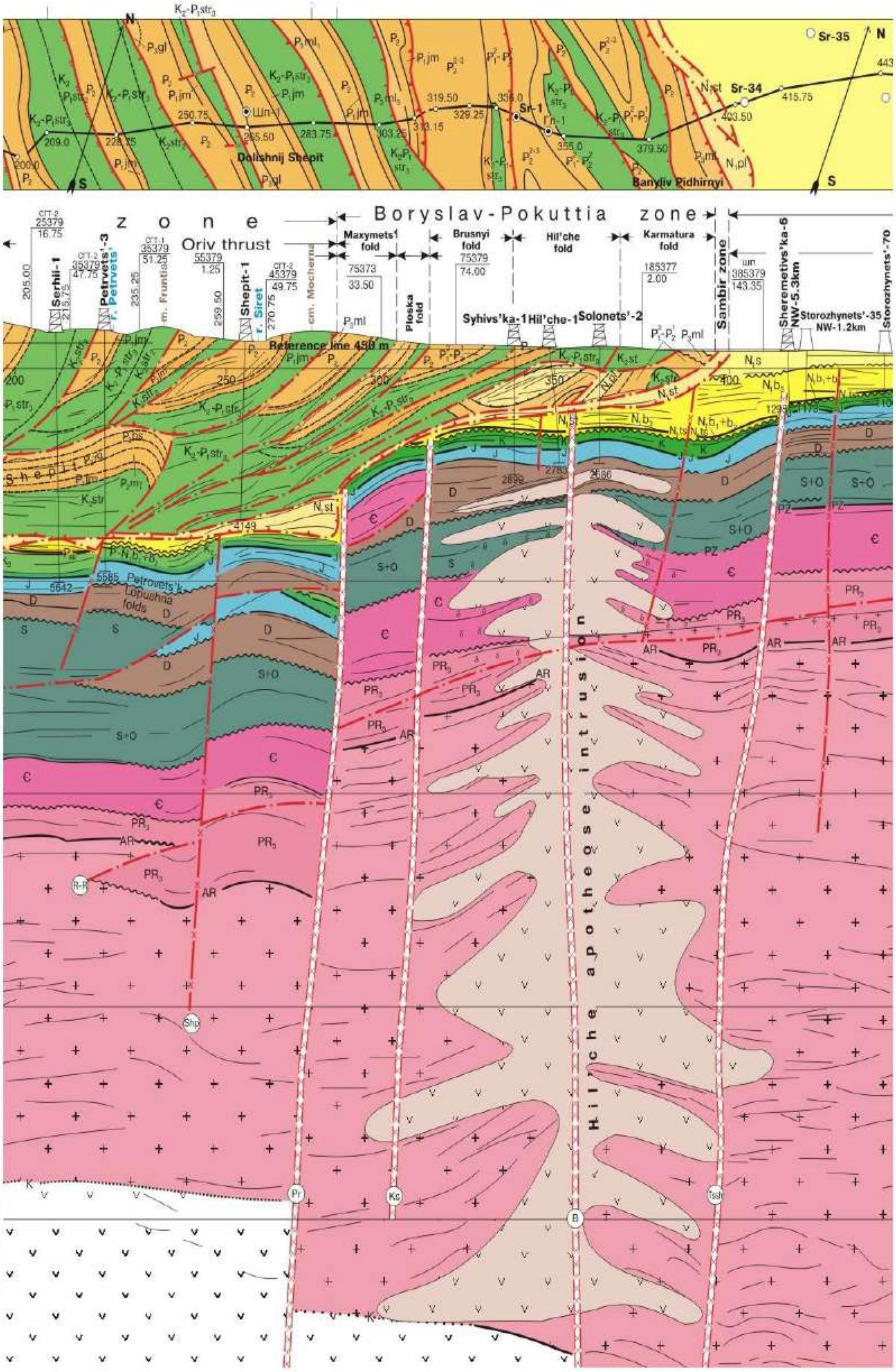


Fig. 5. Detailed structure of the earth's crust of Bukovyna according to data from the profile RP-5 (fragment) in the Precarpathian deep fault zone [Sheremeta, 1999]. Above is a fragment of the detailed geological map in the profile zone. Conventional notations see in Fig. 3, *b*.

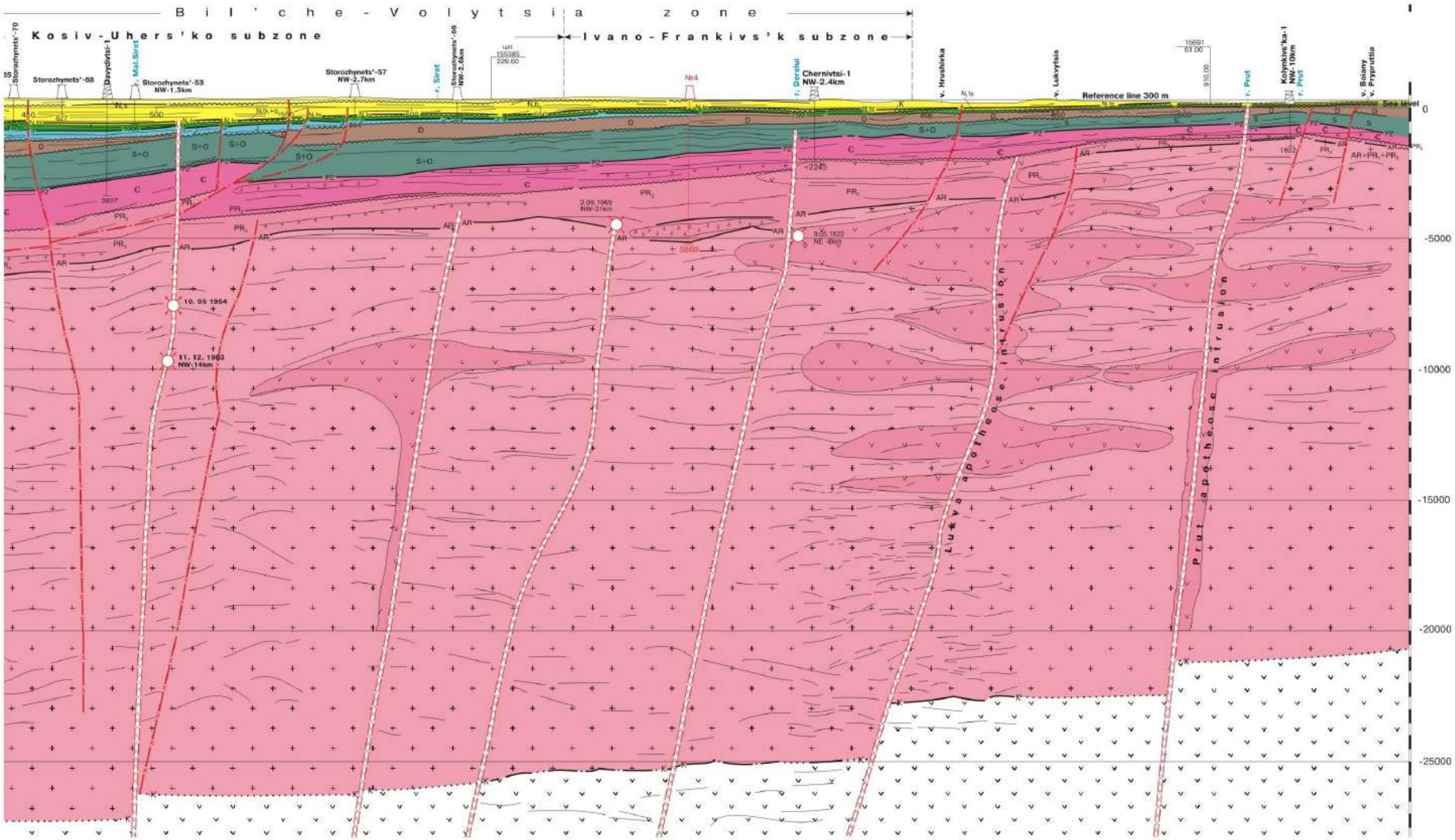


Fig. 6. Detailed structure of the upper (at depths of 0–30 km) horizons of the Earth's crust of Bukovyna according to data from the profile RP-5 (northeastern part – the Carpathian foredeep and the edge of the East-European craton) [Sheremeta, 1999]. Conventional notations see in Fig. 3, *b*.

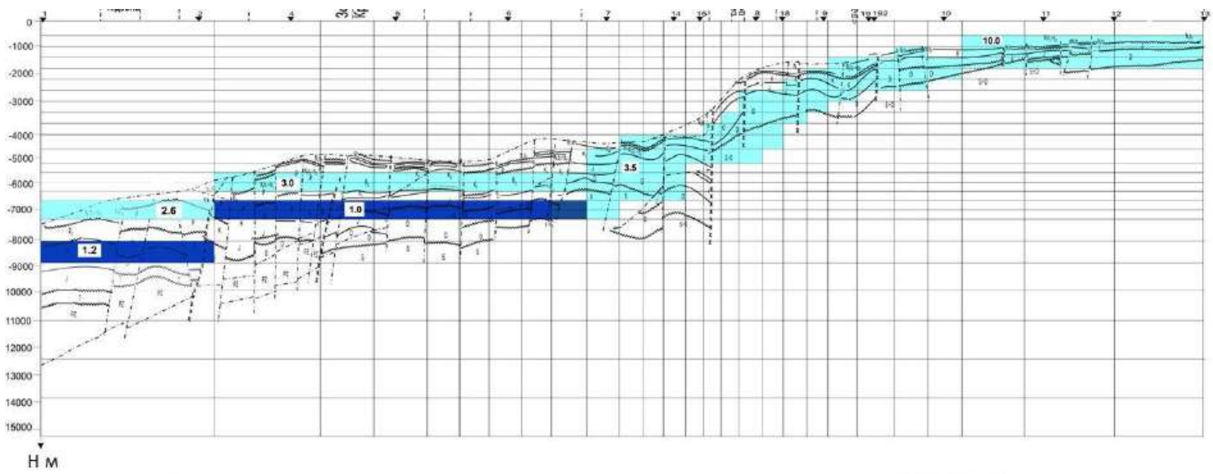


Fig. 7. Deep geoelectric section along the profile RP-5 on the results of 2D inversion of MTS data (V. I. Tregubenko [Lebid et al., 2009]). Geological basis according to [Sheremeta, 1999] (see Figs. 3–6).

Taking into account the data of studies on the paleogeodynamic regimes of the earth's crust of the southwestern edge of the East-European craton ([Kruglov et al., 1985; Boyko et al., 2003; Krupskyy 2001, 2020; Nakapelyukh et al., 2018] and others), in general, it can be said that the structure of the crustal basement in the profile zone is very similar to the structure of the sides of known large grabens (for example, Dnipro-Donetsk). Therefore, there is reason to assume that this structure of the basement of the Carpathians already partially took place here in pre-Alpine (pre-Carpathian) times. In the process of thrusting of the Carpathian covers over the edge of the craton, this structure acquired its modern form.

In more detail, we will consider the structure of the upper parts of the Carpathian autochthon on the territory of Bukovyna in connection with its oil and gas bearing.

As for the comparison of the profile RP-5 with the DSZ-RWCM RomUkrSeis profile [Starostenko et al., 2020; Amashukeli, 2021] (taking into account the relatively smaller spatial resolution and detailedness of the latter), then a not bad matching is observed regarding the zone of the Carpathian thrusts and the Mesozoic below them (RP-5) and the zone of rocks with a rather low (5.35 km/s) P-wave velocity (RomUkrSeis), extension of the Tesseire-Tornquist zone, thickening of the middle crust here. The configuration and the location of the Moho border are somewhat less match here. These and other results of the comparative analysis of these profiles will be the subject of further research.

Oil and gas bearing of Bukovyna and oil and gas prospective structures

The oil and gas bearing of the territory of Bukovyna has been not yet fully explored. Several oil and gas deposits (fields) are known here [Atlas…, 1998; Sheremeta et al., 2004]: Yabluniv, Pylypiv, Debeslavtsi, Hutsuliv, Kosiv, Kovalivka, Chornoguzy, Sheremeta, Lopusha; they are located in the southeastern part of the Boryslav-Pokuttia zone of the Carpathian foredeep. More deposits have been discovered a little further to the north-west, in the Pokuttia Carpathians (the well-known Nadvirna oil and gas bearing region, the Bystrytsa, Pniv, Pasichna, Dovbushany, Mykulychyn, Bytkiv-Babche deposits and others).

Systematic seismic surveys in the Pokuttya-Bukovyna Carpathians have been conducted since 1969 [Cheban, Lyashchuk, 2007]. In 1970, the Lopushna anticlinal structure was discovered in the autochthon of the Carpathians [Pylypchuk et al., 1985; Sheremeta et al., 2004]. This was the basis for the continuation in 1971–1973 of seismic surveys and drilling of the Lopushna-1, -2 and Sergii-1 wells.

As a result of these works, an initial structural map of the Mesozoic reflective horizon, associated with the boundary within the Mesozoic stratum, was constructed, but it did not match well enough with the drilling data. The problems of reliable tracking of structures based on seismic data in this area were as follows [Sheremeta et al., 2004]. The sole of the allochthonous horizon is identified on seismic sections by correlation of the boundary, that separates well-defined autochthonous horizons from the seismic record complicated by waves-obstacles. In the autochthonous complex, the roof of the Cretaceous layer appears as a distinct horizon with sufficient reflection energy, but this horizon is identified laterally with difficulty on seismic profiles. The behavior of the Cretaceous roof is unstable, as it is a paleo-relief, with inconsistent layering, complicated by intense erosion, so it is not entirely suitable for mapping. Due to the small thickness of this horizon and the insufficient vertical resolution of seismic records at these depths, the Cretaceous roof can sometimes be mistaken for the Jurassic roof. This is mostly observed in the central part of the anticline. That is why the deep structure of the Lopushna deposit is most fully and clearly displayed on the structural map of the reflective horizon *J* (roof of the Jurassic). Besides this, the results of special studies showed that the area of the Lopushna deposit is characterized by a complex gradient of velocities $V=f(t)$ and the regularity of changes in the velocities of elastic waves is determined by the lithology and thickness of thrust rocks, as well as the structural form of the autochthon, these results were used for refined structural constructions.

After studying the described and other features of the propagation and reflection of seismic waves in this area and conducting research in the arch part of the detected uplift (described in the previous subsections of this article), new refined structural constructions were carried out on the reflecting horizon *J* (roof of the Jurassic) [Sheremeta et al., 2004] (coincided with the data of subsequent drilling with an accuracy of 0.5 % (20 m)) and new exploration wells were recommended. In the process of drilling the Lopushna-3 well, recommended by us in 1983, from a depth of 4303 m, an uncontrolled ejection of oil and gas occurred during the penetration of the autochthon (Cenomaniansediments of Cretaceous). This is how the Lopushna oil field was discovered, located 12–14 km to the northwest of the profile RP-5 (see Figs. 8 and 9) [Atlas…, 1998; Sheremeta et al., 2004]. On the example of the structures of the zone of this deposit (Fig. 8), also taking into account the data from [Sheremeta et al., 2002, 2004, 2011; 2019; Pylypchuk et al., 1984; Osadchyy et al., 1999; Garasymchuk, 2001; Monchak et al., 2010; Prokopiv, Hrycyshyn, 2012] and others, we will consider in more detail the features of the oil and gas bearing and oil and gas prospects of the Bukovyna subregion.

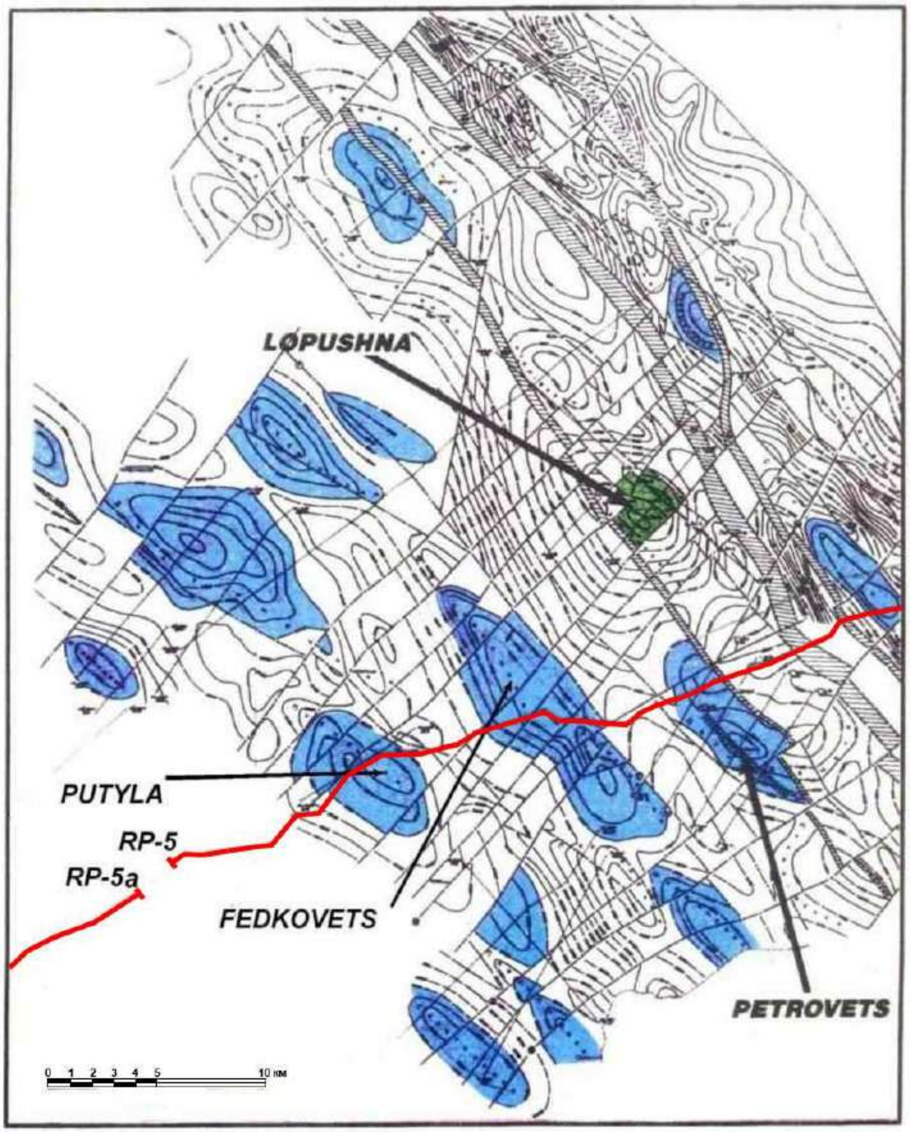


Fig. 8. Structural map of the Pokuttya-Bukovyna Carpathians on the reflective horizon J (roof of the Jurassic) [Sheremeta et al., 2004]. The main folds in the subthrust of the Carpathians in the area of the profile RP-5 and Lopushna oil field are marked (explanation in the text).

Geologically, the deposit is located in the Pokuttya-Bukovyna Carpathians, within the junction of the Skyba Zone of the Folded Carpathians and the Boryslav-Pokut tia Zone of the Carpathian foredeep (Fig. 8). The oil and gas deposits of the field are confined to the Lopushna-Petrovets zone of folds adjacent to the Pericarpathian fault from the southwest in the subthrust of the Carpathians, to Upper Jurassic limestones (J_{3nz}), Albian-Cenomanian (K_{al-c}) and Neogene/Paleogene (N_1P_2) sandstones, i.e. to the foreland sediments under the Carpathian orogen (see Figs. 5, 8, 9) [Atlas…, 1998; Sheremeta, 1999; Sheremeta et al., 2004]. Stebnyk and flysch formations of the Maxymets', Ploska and Brusnyy folds of systems of the Pokuttia folds and the Skyba zone are superimposed on them (Figs. 4 and 9). On the roof of the Jurassic sediments, the Lopushna structure is a brachyanticline of the Carpathian extension, with the dimension of 6×3 km and an amplitude of elevation of 150 m. It is divided into 7 blocks by lengthwise and transverse faults [Atlas…, 1998; Sheremeta et al., 2004].

According to our [Sheremeta, 1999; Sheremeta et al., 2004] structural constructions with taking into account the data of multiple tracing of boundaries in wells. (see Figs. 5 and 8), the Lopushna structure is located within the downthrow step (downthrow side of the Pericarpathian downthrow) and is bounded to the northeast by the near-fault graben. Its southwestern part is complicated by the Shepit downthrow with an amplitude of 100–500 m, which divides the anticline into two lengthwise blocks, Lopushna itself (the central part and the northeastern side), within which the deposit is open, and Biskiv (south-western side).

On the refined structural map (Fig. 8), the Lopushna anticline is depicted with a northeastern side, which is only complicated by an upthrow. On the reflecting horizon J, Mesozoic sediments dip from (–3.350)–(–3.400) m in the vaulted parts to (–3,900)–(–4,200) m in the periclinal parts. Within the southwestern side – up to (–4500)–(–5600) m. The Lopushna structure is complicated by three vaults: the northwestern part with one vault with isogypsum at –3350 m, in which wells Lopushna-11 and –32 are located; the southeastern one with isogypsus –3400 m and with two vaults, in which wells Lopushna-3 and -4 are located, respectively. Between them there is a narrow synclinal depression of a whimsical shape in plan, which causes the absence of oil and gas deposits in wells Lopushna-9, -31.

Lengthwise dislocations (from the northwest to the southeast) are inherited (judging by their penetration into the deeper horizons of the crust) from older thrusts that arose as a result of Mesozoic and Paleozoic (Hercynian) processes, although, obviously, they were partially deformed to the present state and by the Alpine/Carpathian compression.

The structure is also divided into separate blocks by numerous transverse faults of shear-slip kinematics (Fig. 8) with amplitudes of horizontal and vertical displacements of 20–200 m. These faults deform the lengthwise shear-slip faults in northeast-southwest direction, splitting them into separate parts and displacing them. Therefore, transverse faults were later in time of formation. They were formed, apparently, as a result of the adaptation of structures to changes of geodynamic regimes and became more active during the Neogene, but in most cases before the formation of the Carpathian nappes-thrusts, because they do not disturb the allochthon complex overlying them [Shpak et al., 1979; Sheremeta et al., 2001]. They were and are the paths of hydrocarbon migration. The process of filling traps with fluids continues at the current stage. Here we have a shining example of widespread in the world, including in the Carpathian region of Ukraine, keyboard-like (horst-graben) tectonics, caused by complex geodynamic regimes of compression-extension-shearing and by the rheology of the crustal horizons lying below, by the influence of tectonic stresses and geothermal processes and hydrodynamics [Yarotskiy et al., 2020].

The depth structure of the Lopushna structure is shown on the geological section (Fig. 9). The Lopushna-3 well revealed the thick flysch allochthon of the Boryslav-Pokuttia zone (0–3700 m) and molasses of Sambir (3700–4045 m) zone of the Carpathian foredeep. In the autochthon, the well passed the Paleogene (?) and lower Baden (4045–4080 m), upper (4080–4205 m) and lower (4205–4245 m) Cretaceous and Jurassic rocks (4245–4391 m), and the wells Biskiv-1, Lopushna-2 and Lopushna-5, having passed through the full thickness of Jurassic sediments, reveal Paleozoic rocks (Devonian?) at depths of 5210–5369 m, 4535–4723 m, and 4920–4928 m, respectively.

When testing the well Lopushna-3 in 1984, from Cenomanian sandstones lying at a depth of 4180–4199 m, an inflow of oil was obtained with a flow rate of 300 m^3/day on an 8 mm fitting, the gas factor was 200 m^3/day [Paliy et al., 1986]. This fact testified to the discovery of the Lopushna oil and gas field, the first in the Carpathian underthrust. After that, wells Lopushna-5, -9, -11, -30, -32, Biskiv-1 were drilled, and later wells Lopushna-10, -12, -35. Hydrocarbon deposits were discovered by wells Lopushna-3, -4, -8, -11, -30, -32.

The modern model of the Lopushna deposit is a tectonically shielded trap, because consideringthe main lengthwise faults, the structure can be represented as a horst in Mesozoic sediments. The seal for the deposits are first of all salt-bearing and clayey rocks of the molasses of the Sambir zone and argillaceous marls of the Senon. Clayey sediments of the Upper Baden age, the thickness of which reaches up to 900 m within the graben, also serve as a seal. Such a trap model, as on the Lopushna structure, was established for the first time and is the only productive one in the Bil`che-Volytsia zone of the Carpathian foredeep and, in particular, in the Carpathian subthrust

For the deposit the presence of three reservoir complexes is inherent, namely: Neogene/Paleogene sandstones (N_1P_2), Albian-Cenomanian sandstones (K_{al-s}) and Upper Jurassic limestones (J_3^{nz}).

Lower Baden and Paleogene (platform) sediments are represented in the upper part (Paleogene) by sandstones and in the lower part by argillites and clayey marls. Upper Cretaceous sediments are represented by limestones, organogenic-clastic calcareous Senon-Turonian marls and oil-saturated Cenomanian sandstones. Lower Cretaceous sediments are represented by dense mudstones with thin layers of siltstones and fine-grained sandstones. Jurassic sediments are represented in the upper part by dense highly cracked and loose chalk-like limestones, in middle part by dolomites and the lower part by sandstones, mudstones and siltstones. Paleozoic sediments are represented by dense and medium-solidity argillites, slightly cracked, with local slip planes.

Geodynamics of the subregion and its reflection in the deep structure of the crust and in relief

On the basis of the structure of the earth's crust of Bukovyna presented above based on data from the profile RP-5, we will briefly consider the geodynamic processes of its formation and their reflection in the relief. Detailed consideration of these issues, as well as the features of the reflection of the geodynamic processes of the formation of the earth's crust of the subregion in its relief and the features of the local seismotectonic process goes beyond the scope of this article and requires a separate detailed presentation.

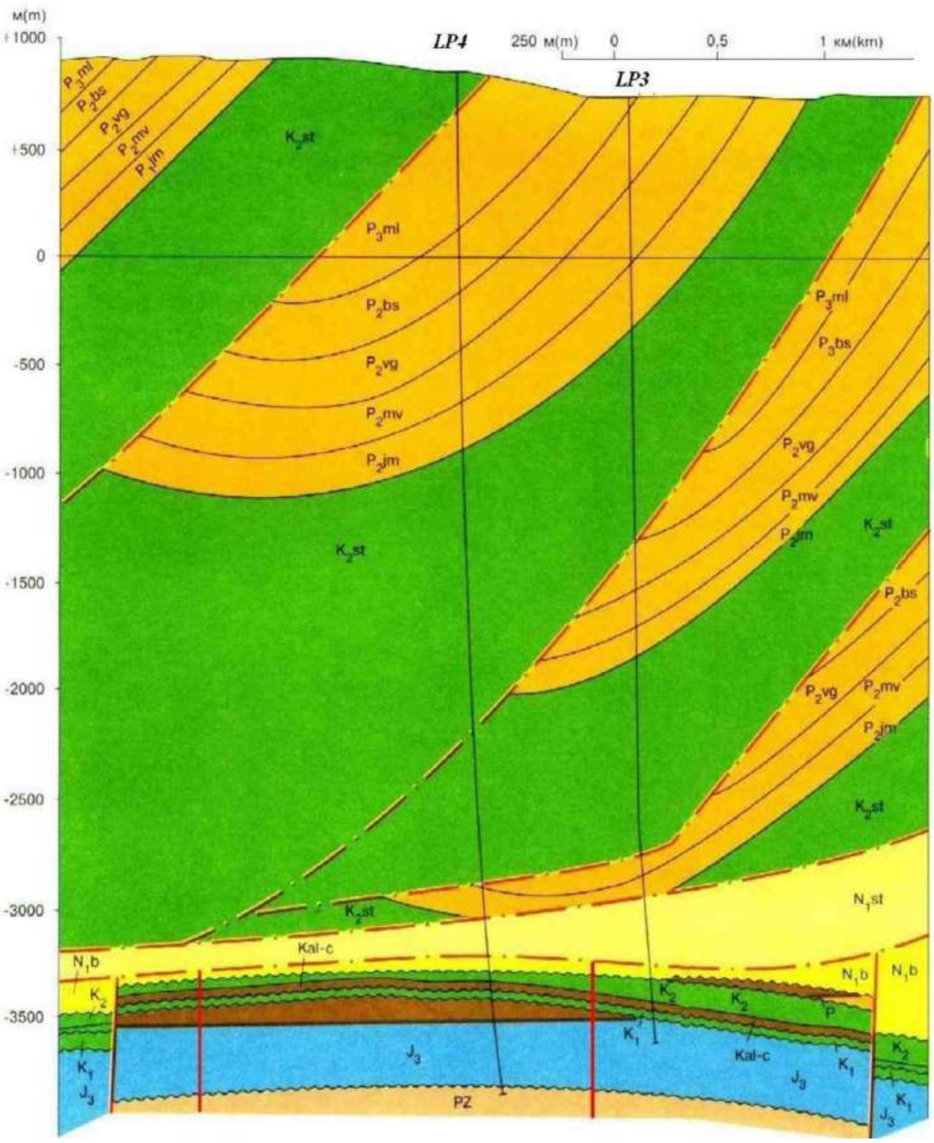


Fig. 9. Geological cross-section of the Lopushnyan deposit (according to R. T. Trushkevych with additions of P.M. Sheremeta) [Sheremeta et al., 2004].

Presented above structure of earth's crust of Bukovyna according to data from the profile RP-5 indicate its complex geodynamic evolution over geological time, the change of geodynamic regimes here at various stages of this evolution, which we have already partially noted. In particular, established stepped deepening of the pre-Neogene bed of the Carpathians and the thrusts in the Paleozoic and Mesozoic, in our opinion, were caused both by the spreading of the Tethys paleoocean and by the convergent and divergent processes [Sheremeta et al., 2004, 2019]. The thickening of the lower horizons of the Bukovyna crust along the profile RP-5 in the central part under the Carpathians indicates the existence here in the Alpine and post-Alpine times (in the last 20–25 million years) of a regime of general compression of the crust in the cross-Carpathian direction.

The same is indicated by the fold bands of the Carpathian extension in the subthrust of the Carpathians, which were formed under the action of the Alpine/Carpathian compression and thrusting of the Carpathian covers and nappes on the edge of the East-European craton. And the main indicator of such compression is the thrust-covers themselves, which by vertical wedge with a thickness of 10–12 km in the southwest (the area of Mt. Chyvchyn) up to 4 km to the northeast (in the zone of the Pericarpathian deep fault) overlap the edge of the platform (see Fig. 4) and are completely wedged further at a distance of 9–10 km to the northeast of it, in the Boryslav-Pokuttia zone of the Carpathian foredeep, in zone of the Chereshenka fault.

The complex small-block structure of subthrust horizons of the crust, studied in the territory of Bukovyna and, in particular, in the area of the Lopushna oil field, partially may be connected with the action on the lower crust of the eastern, "terrane" component of tectonic stress. Because it is known [Nazarevych A.et al., 2023] that this pressure (and the corresponding uplift of the day surface) is manifested in the depths of the crust in this segment of the Ukrainian Carpathians, in particular, close to the studied subregion, in the territory of Solotvyno depression, the eastern part of the Transcarpathian trough [Lozynyak et al., 2011], and besides since the time of magmatic activation in Transcarpathians (Sarmatian – Pannonian, 13-11 million years ago).

The influence of asthenolitic processes and "crocodile tectonics", which are expressly manifested in the deep structure of the crust of the western and partly central segments of the Ukrainian Carpathians, can be traced here weakly, probably indirectly.

Originality

Formulating the originality of the researches, presented in the article, it can be stated, that the peculiarities of the deep structure, geodynamics, seismicity and oil and gas bearing of the Bukovyna lithosphere were determined based on the data of the regional profile RP-5, taking into account new data from oil and gas exploration studies in the subregion and data on various components of the geodynamic process in the whole Carpathian region of Ukraine. The oil and gas prospects of a number of deep folds of autochthonous Mesozoic rocks in the subthrust of the Pokuttia-Bukovyna Carpathians have been predicted and confirmed.

Practical significance

The researches results make it possible to more clearly justify the directions of oil and gas exploration in the subregion.

Conclusions

Summarizing what has been said, we note the following.

According to the data of a complex of field studies on the regional profile RP-5, specialists of WUGPE obtained fundamental, unexcelled world-class results concerning the study of the deep structure of the earth's crust of Bukovyna [Sheremeta, 1999; Sheremeta et al., 2004]. In particular, the structure of the Carpathian thrusts-nappes of the Porkulets, Chornogora, and Skyba zones of the Folded Carpathians and Boryslav-Pokuttia zone of the Carpathian foredeep was studied in detail, including thrusts and folds of various depths. A stepped dip in the zone of the profile RP-5 of the edge of the East-European craton on the territory of Bukovyna under the Carpathians was established and traced in detail (basically similar to that in other segments of the Ukrainian Carpathians. The presence here of a few dislocated autochthonous layers of Mesozoic rocks under the Carpathian thrusts is discovered. In these horizons, several bands of folds of the Carpathian extension were discovered, some of them, in particular, the Lopushna fold, are associated with open oil and gas deposits. The extension of the ancient trans-European Tesseire-Tornquist rift zone is also traced here, between Selyatyn fault in the southwest and Pericarpathian fault in the northeast. The thickening of the horizons of the lower crust under the axial part of the Bukovyna Folded Carpathians was revealed.

Fundamental results concerning the study of the deep structure of the earth's crust of Bukovyna were also obtained from the data of seismic survey works in the neighboring areas in the territory of the subregion. Based on these data, a number of sections of the Carpathian and orthogonal extension, maps of the surfaces of subthrust structures in the crust of Bukovyna were constructed, the structure of deep folds and other oil and gas promising structures was traced in detail, which made it possible to discover a number of hydrocarbon deposits in the subregion and promises such discoveries in the future, in particular, in the underthrust of the Folded Carpathians.

As for the others fundamental results of the described works, on them in the pre-Carpathian part of the profile the 2 buried ancient “seismofocal” zones of different centuries of formation and different vergence were traced (studied in detail by S. G. Slonytska based on the results of the analysis of gravimagnetic fields [Slonytska, 2017; Sheremeta et al., 2019]), as well as a number of apophysis-like intrusions. Features of the distribution of electrical conductivity in the depths of the lithosphere of the subregion were investigated by the MTS method (V. I. Tregubenko, B. T. Ladanivskyy).

The structure of the crust of Bukovyna, established from the data of the profile RP-5, generally corresponds well with the data of the DSZ-RWCM profile RomUkrSeis that was worked out much later (2014), laid parallel to it and literally nearby (20–35 km to the east) [Starostenko et al., 2020; Amashukeli, 2021].

As a result of a comprehensive analysis of the listed data, we traced the influence on the modern structure of the crust of the subregion and its relief of the characteristic features of the local Alpine geodynamic process, the Alpine/Carpathian compression of the lithosphere in the northeast direction orthogonal to the Carpathians, which caused the corresponding thrusts of the allochthon on the previously steeply immersed in the south-western direction in the train of pre-Alpine rift geodynamic processes the edge of the East-European craton. The impact on the modern structure of the crust and the relief of the subregion of the recently discovered terrane component of the regional geodynamic process, associated with the eastward movement of the Earth’s crust of the Transcarpathian depression, the northeastern end of the Alkapa terrain, is also briefly traced.

The increased conductivity of the Mesozoic autochthonous layers underlying the Carpathian thrusts in the territory of Bukovyna (and probably in all the Carpathians), discovered by the results of MTS, and therefore its noticeable wateriness we consider as one of the important factors of the easy thrusting of the Carpathian covers and nappes on them, noted according to tectonostructural data (the so-called anti-friction effect “damp sponge”).

Presented in the article and other currently available data on the structure and oil and gas bearing of the earth's crust of the Bukovyna subregion indicate a high prospect concerning to oil and gas presence in the autochthon of the Pokuttia-Bukovyna Carpathians. In particular, the priority objects for the discovery of even larger deposits than Lopushna are the Fed`kovets and Putyla folds, located in the same transverse tectonic block, and the thickness of the Paleogene sediments of the autochthon within the latter, according to seismic data, reaches 300 m. Along with the traditional structures, anticlinal and tectonically shielded traps in various structural horizons of the Carpathian thrusts, connected in particular with the evolution of the seismotectonic processes in the region, areas where injective structures have been discovered are of exploration interest in terms of oil and gas, because as a result of the penetration of magma up the section, the Mesozoic-Paleozoic sediments are deformed, forming traps for hydrocarbons. Deeper structures in the zone of the surface of the basement and in its mass (both in the basement of the Carpathians and on the adjacent edge of the craton) are also oil and gas promising. The research considers the presence of subvertical and subhorizontal fractured zones of tectonic genesis, where deep hydrocarbons can migrate and concentrate, including mantle inorganic origin.

Considering that there are many landslide-prone areas in the territory of Pokuttia and Bukovyna, important and ecologically dangerous national economic objects (for example, reservoirs of the Dniester Cascade HPP and HAPP, oil and gas production zones), where a number of earthquakes have recently been recorded, the noted local features of structure of the Earth’s crust, as well as the presence of local seismicity should be taken into account when assessing the seismo-ecological hazard in the subregion.

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ЗЕМНА КОРА СХІДНОГО СЕГМЕНТА УКРАЇНСЬКИХ КАРПАТ В ЗОНІ РЕГІОНАЛЬНОГО ПРОФІЛЮ РП-5: БУДОВА, ГЕОДИНАМІКА, НАФТОГАЗОНОСНІСТЬ

Мета роботи – широко висвітлити для наукової спільноти і детально проаналізувати будову та нафтогазоносність літосфери Буковини (східної частини Карпатського регіону України) за унікальними даними по регіональному профілю МВХ-СГТ РП-5 та по сусідніх регіональних профілях з залученням інших геолого-геофізичних даних. Методика передбачає детальний комплексний аналіз глибинної будови і нафтогазоносності та нафтогазоперспективності регіону та його окремих зон на основі сейсморозвідувальних даних по регіональному профілю РП-5 та сусідніх нафтогазоносних і нафтогазоперспективних районах з залученням комплексу геолого-геофізичних даних. Результати. У зоні профілю РП-5 детально простежено залягання в земній корі Буковини осадових товщ і покривів Складчастих Карпат, Передкарпатського прогину і краю Східноєвропейської платформи, включно з різноглибинними ярусами карпатських насувів і складок. Встановлено ступінчасте занурення тут краю Східноєвропейської платформи під Карпати (загалом подібно, як і в інших сегментах Українських Карпат). Встановлено наявність тут під карпатськими насувами малодислокованих автохтонних шарів порід мезозойського віку. У цих горизонтах виявлено кілька смуг складок карпатського простягання, до деяких з них, зокрема, до Лопушнянської складки, приурочено відкриті нафтогазові родовища. Виявлено потовщення горизонтів нижньої кори під осьовою частиною Буковинських Складчастих Карпат. У передкарпатській частині профілю простежуються дві заглиблені древні "сейсмофокальні" зони різного віку утворення та різної вергентності (детально дослідила С. Г. Слоницька за спеціальними методиками), а також кілька апофізоподібних інтрузій. У результаті комплексного аналізу простежено вплив характерних рис місцевого альпійського геодинамічного процесу – альпійського (карпатського) стиску літосфери в ортогональному до Карпат північно-східному напрямку і відповідні насуви алохтону на попередньо ступічасто занурений у південно-західному напрямку в результаті подібних до рифтових преальпійських геодинамічних процесів південно-західний край Східноєвропейської платформи. Наукова новизна. Встановлено особливості глибинної будови, геодинаміки, сейсмічності та нафтогазоносності літосфери Буковини за даними по регіональному профілю РП-5 з урахуванням нових даних нафтогазопошукових досліджень у субрегіоні й даних про різні складові геодинамічного процесу в усьому Карпатському регіоні України. Спрогнозовано і підтверджено нафтогазоперспективність ряду глибинних складок автохтонних мезозойських порід у піднасуві Покутсько-Буковинських Карпат. Практична значущість. Результати досліджень дають можливість чіткіше обгрунтовувати напрями нафтогазопошукових робіт в субрегіоні.

Ключові слова: Українські Карпати; Буковина; регіональний профіль РП-5; тектоніка; геологія; геодинаміка; нафтогазоносність.

Received 12.10.2023