УДК 550. 24. 035 DOI: https://doi.org/10.24028/gj.v45i2.278310

Transcarpathian Depression: Study of Low-Velocity Zones in the Earth's Crust Based on the Seismic Regional Profiles Data

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Received 1 February 2023

Transcarpathian depression (TD) is located in the junction zone of the eastern margin of ALCAPA terrain and the northern part of Tisza-Dacia one, buried under thick Neogene molasses. The Earth's crust structure of the TD is not clearly understood.

The purpose of this work is to refine the TD crust structure and identify low-velocity zones by interpreting wave images obtained from WARR PANCAKE profile data using the finite-difference reflection/refraction migration method.

The crustal domain beneath the TD is interpreted to be limited from southwest by a fault gently southwest dipping, traced from Pieniny Klippen Belt on the surface. Within domain two suture zones being the Alpine Tethys ocean remnants and cemented the European plate and ALCAPA microplate, were distinguished: Piemont-Liguria and PKB ones, as well as a rootless fragment of ALCAPA terrain. The Outer Carpathians thrust belt of 13 km depth borders the TD by subvertical Transcarpathian fault. The crust structure of the Pannonian segment is interpreted to be a pile of thick- and thin-skinned basement nappes of the Tisza terrain and cover nappes with superimposed younger extensional structures.

High-reflectivity and low-velocity zone at depths of 10—20 km is identified. The zone follows the pattern of isotherms in the temperature range of 300—500°. On the deep seismic sounding (DSS) Chop—Velykiy Bychkiv profile, running along TD and crossing the PANCAKE line, two low-velocity zones were also distinguished. Published data on numerical and physical modeling, the deep well cores, as well as fault zones in natural outcrops suggest that the low-velocity zones have increased porosity, fracturing, and fluid saturation. Our results suggest a high hydrocarbon potential of the TD, associated with the low-velocity zones.

Key words: Transcarpathian Depression, DSS, PANCAKE profile, Chop—Velykiy Bychkiv profile, finite-difference reflection/refraction migration method, low-velocity zone.

Introduction. Increasing the hydrocarbon potential in the world is associated with the development of unconventional sources of hydrocarbons, among them the most promising are deposits located at greater (more than 6 km) depths [Lukin, 2014; Ivanov, 2018; Rudko, Sobol, 2020; Murovskaya, 2023]. Low-velocity zones, which are widespread in the

Citation: *Murovskay, A., Verpakhovska, O., Hnylko, O., Chorna, O., & Yegorova, T.* (2023). Transcarpathian Depression: Study of Low-Velocity Zones in the Earth's Crust Based on the Seismic Regional Profiles Data. *Geofizicheskiy Zhurnal, 45*(2), 30—43. https://doi.org/10.24028/gj.v45i2.278310.

Earth's crust and upper mantle of oil and gas regions, may be potential sources of hydrocarbons [Chekunov et al., 1969; Baranova et al., 2011; Korchin et al., 2019]. On the territory of Ukraine, one of the most expressive regions by low velocity zones is the Transcarpathian Depression (TD). The TD originated in the hinterland of the Ukrainian Carpathian orogen — an area of increased heat flow, seismic and tectonomagmatic activity [Liashkevych, 2014; Kutas, 2014; Tretyak et al., 2015; Murovskaya et al., 2018].

Some deposits and numerous manifestations of rare and polymetallic ores corelate with the zones of Neogene-Quaternary volcanism in the TD. Four small methane fields are known in the Miocene molasses of the depression [Kolodii, 2004].

On the basis of deep seismic sounding studies using the correlation method of refracted waves, low velocity zones were identified in the TD Earth's crust [Chekunov et al., 1969], which, according to the results of thermobaric petrophysical modeling, could be the reservoirs of abiogenic hydrocarbons [Korchin et al., 2019]. The northwestern part of the TD is crossed by the DSS (or WARR — wide-angle reflection and refraction) PANCAKE profile [Starostenko et al., 2013; Verpakhovska et al., 2018; Murovskaya et al., 2019]. Using the PANCAKE seismic data, we formed wave image to a depth of 25 km applying the original finite-difference reflection/refraction migration method and distinguish some new features of the TD Earth's crust structure.

The purpose of this work is to refine the structure of the TD crust, identify low velocity zones based on the seismic regional profiles data, particularly on the PANCAKE profile. The relevance of our study is associated with use of modern methods of seismic data processing of regional DSS lines, which allows to get new details of the deep structure of the study area, in particular, information about of low-velocity zones and the prospects for identifying fluid-saturated zones and hydrocarbon reservoirs.

Geological and tectonic background. Transcarpathian Depression (Fig. 1, 2) extends through Eastern Slovakia and Ukrainian Transcarpathia and passes into the territory of Romania. Within its limits, the East Slovak, Chop-Mukachevo, Solotvino and Marmarosh parts are distinguished. In Ukraine there is the Chop-Mukachevo and major part of Solotvino depressions, separated by the N-S trending branch of the Neogene Vygorlat-Guta Volcanic Ridge. The TD locates in the hinterland of the Outer Carpathians and separated from the Outer Flysch Carpathians by the Transcarpatian Fault Zone and Pieniny Klippen Belt (PKB), and from Panonian Basin by the Pannonian Fault Zone, which is traced along the Chop—Beregovo—Vishkovo line by a strip of uplifted basement and magmatic rocks development [Glushko, Kruglov, 1971; Gurskyi, Kruglov, 2004].

The TD shown in [Starostenko et al., 2013] is significantly wider and extends beyond the borders of Ukraine. Fig. 1, *b* shows the updated version of the TD position along the Pancake profile.

The slightly deformed Neogene successions filling of the TD rests on strongly deformed basement formations of Paleozoic, Mesozoic and Paleogene ages. The sedimentary cover of the TD includs marine, lagoonal, and continental volcanic deposits of Miocene, Pliocene and Eopleistocene of total thickness up to 5 km [Lozinyak, Misyura, 2010; Prykhodko, Ponomareva, 2018].

Plate tectonic setting. The TD locates at the junction of the eastern margin of ALKAPA terrane (Central Western Carpathians) and the northern part of Tisza-Dacia one (Central Eastern Carpathians) (Fig. 1). The terranes are considered to be the fragments of the (micro)continents of the Tethys Ocean. They are limited by suture zones (SZ)/accretionary prisms, the remnants of (sub)oceanic basins that were localized between these terranes and between terranes and Eurasia plate [Schmid et al., 2020].

Central Western Carpathians are surfacing in the Western Carpathians outside Ukraine and buried under Neogene deposits of the TD [Hnylko, 2011]. In whole, Central Western Carpathians represent a pile of thick- and thin-skinned nappes of crystalline basement and cover, corresponding to the Austroalpine tectonic system of the Eastern Alps [Plašienka, 2018; Schmid et al., 2020 and references therein].

The crystalline basement complexes of the Central Western Carpathians developed under the Neogene deposits of the Mukachevo part of the TD are exposed by boreholes at 897—4521 m in the area of the cities of Uzhgorod and Chop (the so-called Uzhgorod uplift). They are composed of quartz-micaceous, micaceous-carbonate, filitoid (gray, green-gray, red-brown, violet) schists, marble limestones, and dolomite lenses [Matskiv et al., 2003].

The sedimentary cover of the Central Western Carpathian massif include thin Triassic carbonate rocks with siliceous conglomerates at the base, terrigenous-carbonate Jurassic deposits and marl-sandy dark-colored Cretaceous rocks of the Dulovo and Krichevo complexes, which are unconformably overlain by the «Central Carpathian Paleogene» flysch (which in Ukraine is called the Vulshava suit).

The Central Eastern Carpathians include the Marmarosh Crystalline Massif, dismembered into thick-skinned basement nappes. They are adjacent to the Solotvyno and Marmarosh parts of the TD and, probably, partially form their basement. The Marmarosh crystalline basement is composed of Paleozoic and Precambrian metamorphosed formations, and its cover is consisted of Late Paleozoic and Meso-Cenozoic sediments [Matskiv et al., 2009].

ALKAPA and Tisza-Dacia terranes are cemented with each other and Eurasia plate by units derived from the Alpine Tethys [also called Penninic Ocean: Iňačovce-Krichevo Unit, Pieniny Klippen Belt and Outer Carpathian accretionary wedge. The Iňačovce-Krichevo Unit, formed by Penninic-type complexes build up a major part of the TD basement in the Eastern Slovakia being compised of Permo-Mesozoic up to Eocene sheared and folded, and partly metamorphosed sediments including turbidites and ultrabasic bodies. The Iňačovce-Krichevo Unit continues to the Peri-Klippen zone, which is regarded as a part of the subducted Vahicum (South Penninic oceanic domain). Tectonic unroofing and exhumation of the Penninic complexes in East Slovakian Basin area was a result of a strong extension on the conjugate pull-apart fault sytem [Sotak et al., 1994].

A significant part of the Iňačovce-Krichevo Unit can also be developed on the Ukrainian segment of the TD. This point of view is reflected in the regional tectonic schemes [Schmid et al., 2008, 2020], where the Iňačovce-Krichevo suture zone is shown in the significant part of the Ukrainian Transcarpathia

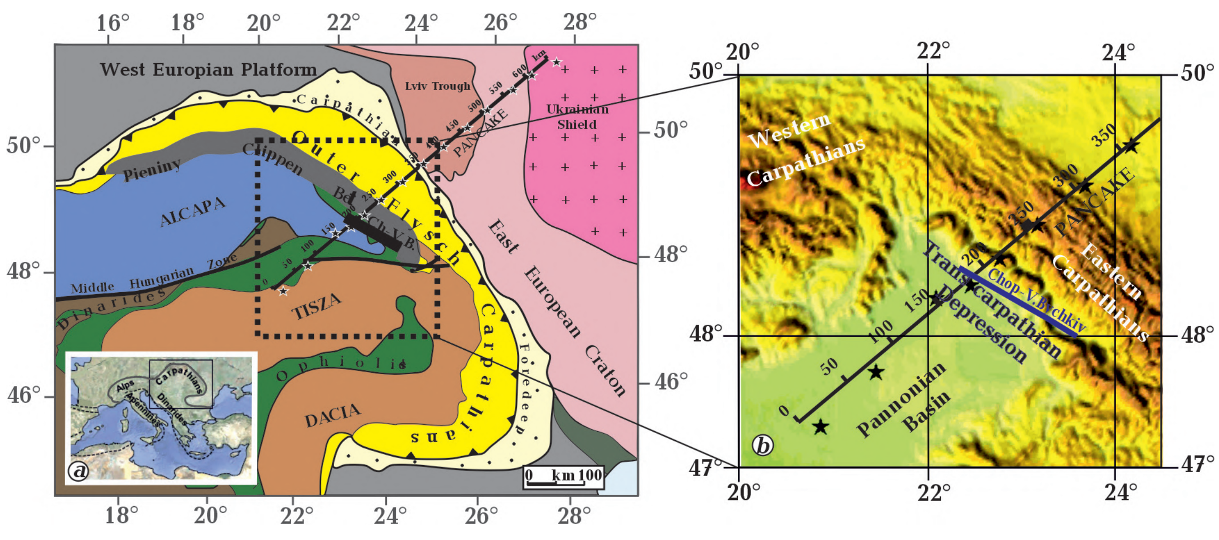

Fig. 1. Tectonic (*a*) and topography map (*b*) for the Carpathian-Pannonian system with location of the PANCAKE and Chop—Velykiy Bychkiv profiles. Modified after [Schmid et al., 2008; Gurskyi, Kruglov, 2004]. Stars denote the shot points (SP).

basement. This zone in the Western Carpathians and the Alps continues respectively Vahic and Piemont-Liguria sutures, and in the Pannonia basement — Szolnok flysch belt, which all belong to the main Alpine Tethys suture limiting the ALCAPA terrane from the North, East and the South.

Pieniny Klippen Belt being of several km wide, but at least of 500 km long represents a complex suture zone of the Alpine Tethys dividing the Cretaceous basement/cover thrust stack of the Central Western Carpathians from the Cenozoic accretionary complex of the Outer Carpathians [Golonka at al., 2006; Plašienka, Soták, 2015]. PKB turns to the SE into the Central Carpathians where wedges between ALCAPA and Tisza-Dacia terranes [Hnylko, 2011; Schmid et al., 2020].

PKB has a block-in-matrix structure, or megabreccia formed by isolated blocks or «klippen» composed of competent Jurassic to Lower Cretaceous limestones surrounded in a soft matrix, consisting of mainly Upper Cretaceous Puchov red marls [Kruglov, 1986; Plašienka, Soták, 2015]. These sediments were derived from the Southern and Nothern Penninic oceanic domains and intra-oceanic continental fragment between them, known as the Czorsztyn Ridge. Its sedimentary substratum has been completely subducted beneath ALCAPA [Golonka at al., 2006; Plašienka, Soták 2015; Schmid et al., 2020].

It is noted [Sviridenko, 1973], in a number of boreholes in the TD Solotvino part, the Cretaceous rocks of the Krichevo suit contain members and interlayers of red marls, which may indicate the marginal facies of the PKB. According to [Lozinyak, Misyura, 2010], the complexes of the PKB were discovered by boreholes south of Khust. Thus, a significant part of the Solotvyno depression basement may belong to the PKB, while the Mukachevo depression is underlain by the complexes of the Central Western Carpathians.

The Outer Carpathians is a thin-skinned thrust belt originated from the Nothern Penninic oceanic domain (including Magura Unit) and Europe-derived flysch units. They consist of several stacked nappes and are considered as the Cretaceous-Neogene accretionary prism formed as a result of subduction of the Carpathian sedimentary flysch basin basement beneath the ALCAPA and Tisza-Dacia terranes. These nappes are filled with allochthonous Jurassic-Neogene mainly flysch sediments uprooted from their original position. The Jurassic-Early Cretaceous basic volcanic rocks are locally presended here in the base of the some flysch successions [Oszczypko, 2006; Golonka et al., 2006, 2019; Hnylko, 2011; Krobicki et al., 2014; Hnylko, Generalova, 2014; Kovác et al., 2016; Nakapelyukh et al., 2017, 2018; Schmid et al., 2020 and references therein].

Neogene volcanic belt is developed in the hinterland of the Outer Carpathians, extending from Slovakia through Ukrainian Transcarpathia to Romania to the Kharghita Mountains along the inner edge of the Flysch Carpathians. The northern branch of the belt is the Vygorlat-Guta ridge, and the southern one is the Keliman-Khargita one. There is a migration of magmatic activity along the belt southward. The volcanic belt is composed of calc-alkaline igneous rocks — mainly andesites, as well as dacites, andesite-basalts, rhyolites, their tuffs and small intrusive bodies of medium acid composition. Its formation is associated with the final stage of subduction of the Alpine Tethys [Seghedi et al., 2001; Konečny et al., 2002; Pecskay et al., 2006].

Deep structure of the Transcarpathian Depression on the DSS Chop—Velykiy Bychkiv profile. Transcarpathian Depression is crossed by two DSS seismic profiles: Chop—Velykiy Bychkiv [Chekunov et al., 1969] and PANCAKE [Starostenko et al., 2013; Verpakhovska et al., 2018] (for location see Fig. 1, 2).The Chop—Velykiy Bychkiv line of 138 km length, carried out by t Institute of Geophysics of Ukraine in 1967, runs along the TD. According to the seismical-and-geological section, the TD crust consists of a number of segments, including the two largest ones that correspond to Chop-Mukachevo and Solotvino depressions separated by Oash fault (Fig. 2).

The upper crust («granite» layer) of Chop-Mukachevo depression is almost twice as thick as that of the Solotvino one. It was suggested that Chop-Mukachevo and East Slovak depressions form a single structure with the Central Western Carpathian massif in their basement. In opposite, Solotvino depression was believed to be underlain by some Paleozoic formations similar to ones of the Outer Carpathians. In Chop-Mukachevo depression under the Paleozoic complex at the depths of 10—15 km, an upper low velocity layer was revealed; and a lower low velocity layer was identified at the crustal base with the top at the depth of 20—24 km and bottom at 24—29 km coincided with Moho discontinuity [Chekunov et al., 1969] (see Fig. 2).

The Chop—Velykiy Bychkiv line, characterized by presence of the low-velocity zones, intersects the PANCAKE at short point (SP) 3. Therefore, we assumed the presence of a low-velocity zone also on the PANCAKE.

Deep structure of the Transcarpathian Depression along the DSS PANCAKE profile. The PANCAKE profile of 650 km length, carried out within the International Project in 2008, runs from the Pannonian Basin to East European Craton and crosses the TD and Ukrainian Carpathians. Registration of seismic waves on the profile was made according to the standard DSS observation system with irregular step between the SP and receivers. The total amount of 14 SP with an irregular 35—50 km step, and 261 receivers deployed with the average step about 2.5 km, were involved. In the result the shot gathers for each SP were obtained, from which the velocity model of the study area was calculated using the ray-tracing method with the SEIS83 program (Fig. 3, *b*).

The wave image of the Transcarpathian Depression Earth's crust by the finite-difference reflection/refraction migration method. We performed additional studies of the TD crust to a depth of 25 km along the PANCAKE segment in the range at km 0—250 distance on the profile, covering the SW part of the Outer Ukrainian Carpathians, TD and Pannonian Basin, using the finite-difference reflection/refraction migration method (hereinafter referred to as the migration method). To apply the migration procedure, the necessary input information, such as velocity model, should be given, for that is was extracted from the obtained ray-tracing velocity model. A specific feature of the finite-difference reflection/refraction migration method is the use of the time field continuation in the computational process. The technique assumes the initial each SP seismograms processing separately and, therefore, it is a «pre-stack» migration. At the final stage, after analysis and comparison of the obtained individual migration images, a summary image of a velocity-contrasting interface between two media along the profile DSS is formed [Verpakhovska et al., 2018, 2021; Verpakhovska, 2021].

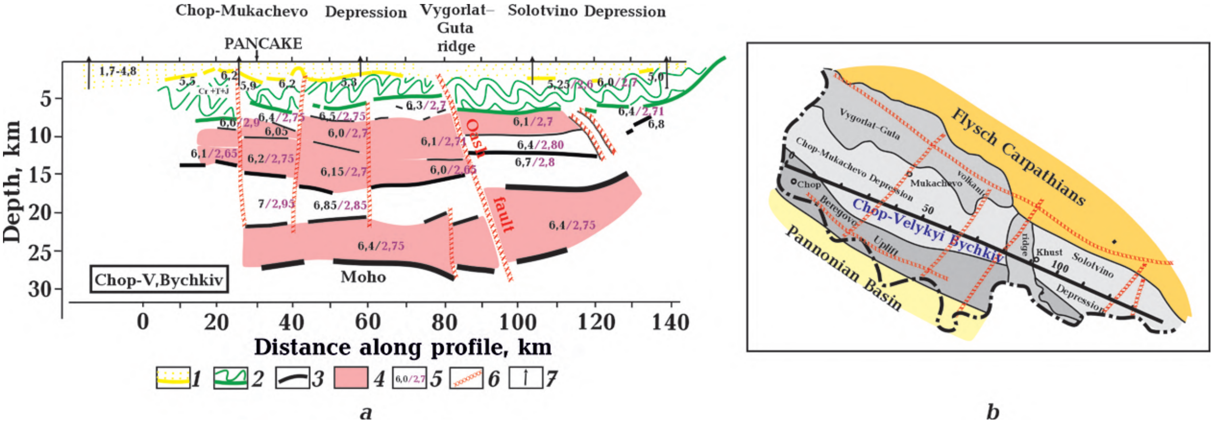

Fig. 2. Deep structure of the Transcarpathian Depression along the DSS-CMRW Chop—Velykiy Bychkiv profile (*a*) and position of the profile line (*b*): *1* — Neogene molasses, *2* — Paleozoic-Mesozoic-Paleogene folded basement of the TD, *3* — seismic boundaries, *4* — low velocity zones, *5* — *P*-wave velocities and corresponding densities, *6* — basement faults according to geophysical data, *7* — boreholls. Modified after [Chekunov et al., 1969; Korchin et al., 2019].

Interpretation of the migration image. For the first time the migration was applied to the whole PANCAKE profile by Verpakhovska et al. [2018], who got wave images for two sharp seismic boundaries — the basement and Moho. The basement image has shown the allochtonous complex of the Outer Ukrainian Carpathians above the basal detachment at ~15 km depth underlain by a high reflectivity strata of Mesozoic-Paleozoic metasedimentary complex related probably to the formation of the Tornquist-Teisseyre Zone. Since our present study is targeted to the TD, we performed an additional interpretation of this part of the PANCAKE by migration to study in more detail the upper part of the cross-section. As a result of migration procedure applying to the PANCAKE data, a wave image of the TD Earth's crust was formed and some of the most striking structural elements were identified (Fig. 3, *a*). We have compared the migration image (Fig. 3, *a*) with the velocity model along the profile, obtained by the ray-traicing modelling [Starostenko et al., 2013] (Fig. 3, *b*), and completed the former by values of velocities, derived from the latter.

At eastern segment of the profile (km 130—250) on the migration image we identified a fault zone gently dipping to SW, which was traced from the PKB on the surface (see Fig. 3, *a*). We have projected the fault zone onto the velocity model (see Fig. 3, *c*). The fault coincides with discontinuities and displacements of seismic boundaries on the velocity model (see Fig. 3, *c*). The Earth's crust to NE from the fault zone has a complex structure, with interrupted reflective and refractive boundaries. The segment of the TD basement at the distance of km 130—170 corresponds to the northeastern edge of the ALCAPA on the tectonic map (see Fig. 1, *a*). We have interpreted it as a rootless fragment of the ALCAPA inside the Piemont-Liguria suture zone (see Fig. 3, *d*).The segment of the migration image at the distances of km 170—220 coisides on the surface (see Fig. 3, *c*) with two complicated SZ between European plate and ALCAPA terraine, being the Alpine Tethys ocean remnants: (1) Piemont-Liguria-Vahic-Inacovce and (2) PKB. The Piemont-Liguria SZ underlays both Slovakia and TD and continues to SW by Szolnok SZ cementing ALCAPA and Tisza-Dacia. On the migrated image the Piemont-Liguria SZ is seen by a lens-shape unrooted fragment, overthrusted by the ALCAPA fragment. The PKB suture zone could be represented on the wave image by Czorsztyn intra-oceanic ridge fragment, wich separated Northern and Southern domains of the Penninic Ocean. At the distance of km 220—250 there is identified the Outer Carpathians thin-skinned thrust belt of 13 km thickness, which borders the TD by the sub-vertical Transcarpathian fault zone at km 220 [Yegorova et al., 2022].

The western segment of the profile at km 0—130 belongs to a wide zone of the ALCAPA and Tisza-Dacia junction (see Fig. 1, *a*) on which the Miocene Pannonian basin was originated. Characteristic features of the structural pattern of the upper crust under the Pannonian Basin are determined by the presence of younger grabens superimposed on the system of gentle thrusts. The structure of the western segment is interpreted as a pile of thick- and thin-skinned Tisza basement and cover nappes.

The high-reflectivity and low-velocity zone is distinguished on the wave image at the depths of 10—15 km and at the distance of km 150—170 gradually sinking to NE up to 20 km depth. The high-reflectivity zone corresponds to low-velocity interval on the PANCAKE velocity model. Above the high-reflectivity zone at 10 km depth, *P*-wave velocities reach 6.22 km/s, while in the zone itself they decrease to 6.20 km/s. Under the zone, the velocity sharply increases and reaches 6.33—6.34 km/s at 17—20 km depth.

We made comparison of the high-reflectivity and low-velocity zone with both surface heat flow and isotherms pattern along the profile. The TD shows an anomalously high heat flow of mantle origin with peaks above the fault zones, being the pass-ways for convective mantle heat flows and mass transfer [Kutas, 2014]. One of the heat flow peaks, of 100 mW/m^2 value, locates in the vicinity of SP3 and marks the Pannonian Fault Zone, which, obviously, is a heat-and-mass pass-

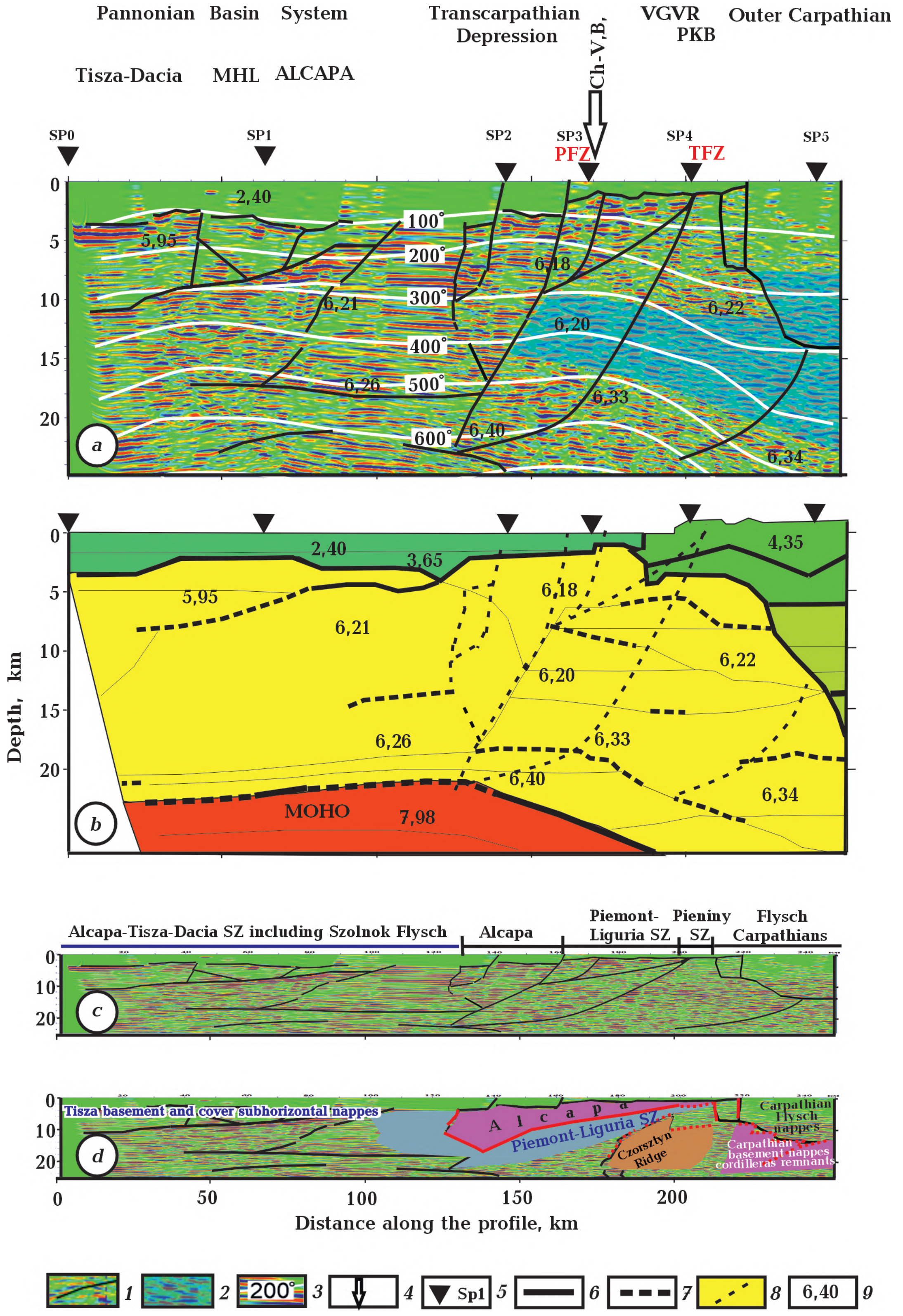

Fig. 3. Wave image of the Transcarpathian Depression Earth's crust along the DSS profile with interpretation elements (*a*), a fragment of the velocity model along the PANCAKE profile using the ray modeling method (*b*) [Starostenko et al., 2013]; The wave image in natural proportions (*c*) allows you to see the real elements of the occurrence of structural elements; schematic tectonic interpretation (*d*); *1* — structural elements obtained on the basis of the wave image; *2* — the increased layering and reduced velocity zone; *3* — isotherms according to the

data [Kutas, 2014]; *4* — intersection with the Chop—Velykiy Bychkiv profile; *5* — shot points and their numbers; *6*, *7* — seismic boundaries according to ray modeling data; *8* — projection of structural elements according to the interpretation of the wave image on the velocity model using the ray modeling method; *9* — seismic velocities. MHL — Middle Hungarian Line, PKB — Pieniny Klippen Belt, PFZ — Perypanonian Fault Zone, TFZ — Transcarpathian Fault Zone, VGVR — Vygorlat-Guta Volcanic Ridge, SZ — suture zone.

way. The high-reflectivity and low-velocity zone starts to trace in the area of the Pannonian Fault Zone, extends to the NE and follows the pattern of isotherms in the range of 300—500 °C. The Physical and chemical processes under the relevant *PT*-conditions contribute to a decrease in velocity of elastic waves and density of rocks, as well to an increase in porosity and fluids' saturation.

Thus, the interpretation of the migration image provides additional useful information on the deep (upper crustal) structure of the study area. Comprehensive consideration of the velocity model and migration image has provided the reconstruction of additional structural elements, among them the high-reflectivity zone, which corresponds to the low-velocity one on the ray-tracing velocity model.

Discussion. *Low-velocity zones in the TD crust were* studied by *geophysical methods*. Rocks in the zones are characterized by reduced density, strength and increased porosity. That was concluded by theoretical calculations, the results of physical modeling on rock samples, geophysical surveys in wells and by the study of deep borehole core [Gintov, 2005; Lukin, 2014; Korchin et al., 2019 and references therein]. According to the results of petrophysical-and-thermobaric modeling along the Chop—Velykiy Bychkiv profile, the upper low-velocity zone at depths of 5—17.5 km, could be composed of decompacted granite-gneiss rocks and the best candidat for the lower one at 18—26 km depth are rocks similar to diorites and basalts under the conditions of high temperatures up to 800 °C [Korchin et al., 2019].

The horizontal layering of the TD upper crust is also known from geoelectrical study [Kováčiková et al., 2016; Burakhovich et al., 2022]. In the central part of the Transcarpathia, at the depths of 7—10 km, the low-velocity zone was recorded, which is represented by a thick (~3 km) tectonically and hydrothermally decompressed fractured zone saturated with high-temperature (~300—400 °C) fluids with high mineralization [Nazarevich, Nazarevich, 2002; Tretyak et al., 2015; Kováčiková et al., 2016].

Rock properties in low-velocity zones. Rock samples under the *PT*-conditions, existed in the zones of low-velosity and low-density and a core from deep boreholes (more than 6 km) [Lukin, 2014], show multiple micro- and macro-destructions. Initialy rigid and dense rocks (granites, quartzites, gneisses, etc.) turned into cracked, porous and brittle ones. Due to the destruction, their porosity increases up to 20 %, and so-called secondary reservoirs are formed, which can provide migration and accumulation of fluids. On the Ukrainian Shield we can observe extremely deformed Precambrian granites and quartzites (Fig. 4), originated and located earlier at significant depths (not less than 8 km), which clearly demonstrate what reservoirs and fluid migration paths in dense rocks can look like.

Cores from a depth of more than 6 km in the central part of the Dnieper-Donets Basin have typical features of the processes of rock decompaction: natural fluid fracturing, tec-

Fig. 4. Fracture zone in strong Precambrian quartzites demonstrates the formation of possible reservoirs of fluids and their migration paths. Photo of S. Mychak.

tonic crushing, intense cleavage. Originaly massive and strong quartzite, sandstones and limestones disintegrate and turn out into thin disc-shaped plates with smudges of oil and condensate when the core is removed [Lukin, 2014].

The Solotvyno part of the TD is adjacent to the Marmarosh Crystalline Massif, wich probably, forms in part its basemen [Glushko, Kruglov, 1971]. Study of thin sections of dense metamorphosed rocks (quartzites and limestones) of the Marmarosh massif from

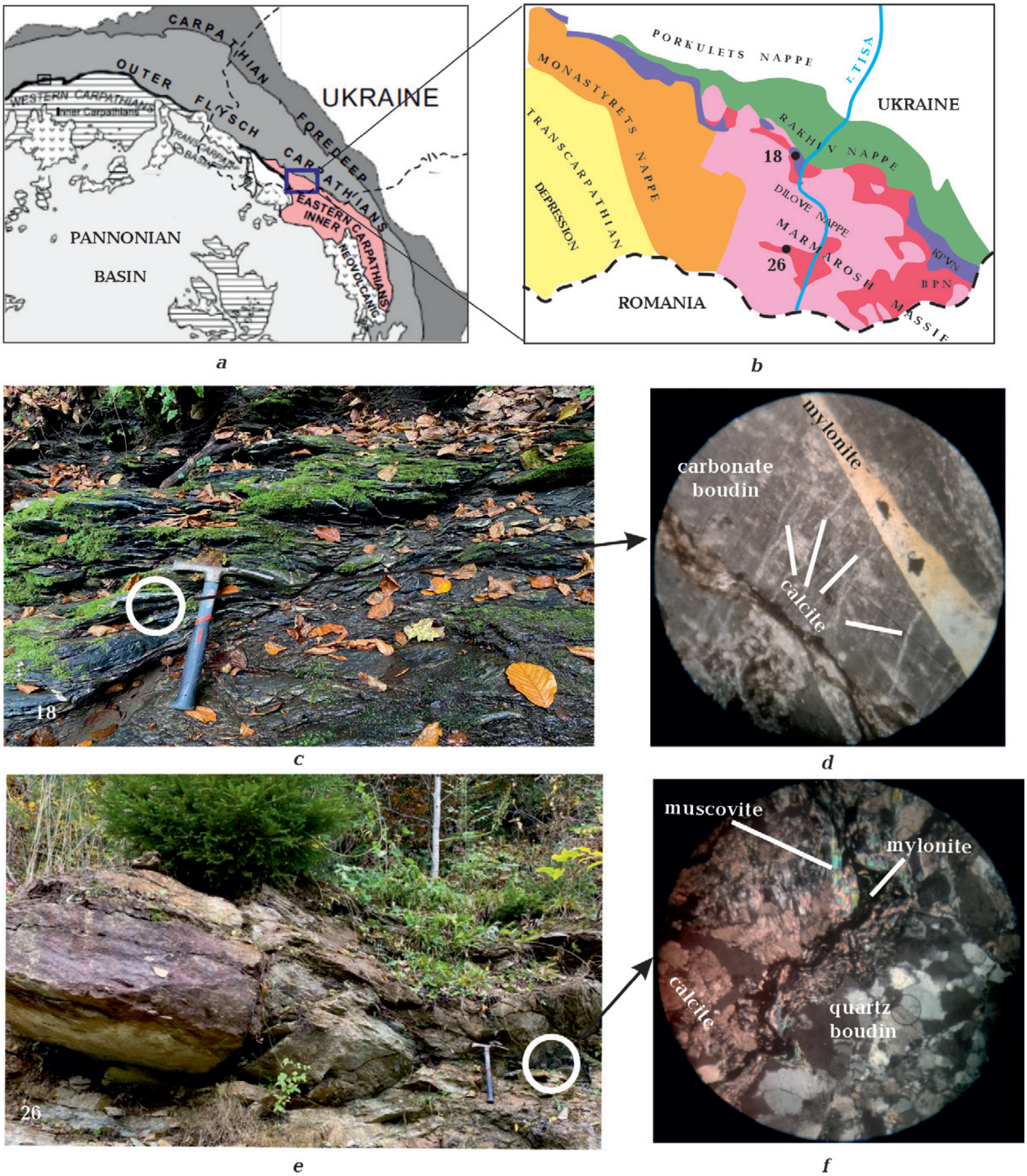

Fig. 5. Fault zones in dense rocks of the Marmarosh massif in natural outcrops and in thin sections. As a result of brittle fracture processes in initially dense rocks (marble limestones and quartzites), a secondary pore space is formed: *a*, *b* — position and numbers (18, 26) of sampling points on the tectonic scheme, *c*, *d* — Lower Cretaceous limestone from a deformation zone in a natural outcrop (*c*) and in thin section (*d*); *e*, *f* — Precambrian quartzite from the deformation zone in a natural outcrop (e) and in thin section (f); BPP — Bilyipotik nappe, RVN — Rachiv and Vezhany nappes.

fault zones, shows a number of structures formed as a result of tectonic fragmentation (microcracks, boudinage, mylonite zones) [Murovskaya et al., 2021] (Fig. 5) leading to an increase of porosity and recrystallization due to action of fluids.

Fluid saturation of the Transcarpathian depression. Zones of low velocity and density are caused by a significant increase in the porosity (up to 20 %) filled with gases and fluids. Numerous mineral springs and gas manifestations testify to the fluid saturation of the subsoil of the TD. The composition of gases is dominated by carbon gases (CO_2 and CH_4). Two sites with a high content of methane are found [Kolodii, 2004]. The high content of carbon gases within the TD indicates the presence of a powerful carbon potential and relevant conditions for hydrocarbons. By an increase of temperature, the content of CO_2 increases as well, and, at the same time, carbon dioxide and methane are enriched with heavy carbon isotops. The revealed pattern in the distribution of carbon gases, methane homologues and native metals indicates their deep origin and the possibility of formation in a wide range of depths under different geothermal conditions [Kutas, 2021].

Conclusions. Transcarpathian depression locates at the junction of the eastern margin of the ALCAPA terrain and the northern part of the Tisza-Dacia one overlain by thick sequences of Neogene molasses. The TD deep structure is not clearly understood. The wave image along the PANCAKE profile, running across the TD was obtained using the finite-difference reflection/refraction migration method. We have performed interpretation of the migration image and made its comparison with the ray-tracing velocity model published earlier [Starostenko et al., 2013].

The Earth's crust domain beneath the TD is limited from the southwest by a fault zone gently dipping southwest, which is traced from PKB on the surface. Within the domain we distinguished two suture zones cementing the European plate and the ALCAPA, which are the remnants of the Alpine Tethys ocean: (1) Piemont-Liguria and (2) PKB ones, as well as rootless fragment of the ALCAPA. The Outer Carpathians thin-skinned thrust belt of 13 km depth borders with the TD by subvertical Transcarpathian fault. The crust structure of the western Pannonian segment is interpreted to be a pile of thick and thin Tisza basement and cover nappes with superimposed younger grabens.

The zone of high-reflectivity and reduced velocity at the depths of 10—20 km has been identified. The zone follows the pattern of isotherms in the temperature range of 300—500 °C. Physical-and-chemical processes under corresponding *PT*-conditions contribute to decrease in velocity of elastic waves, density of upper crustal rocks, as well as an increase in porosity and fluid saturation. On the DSS Chop—Velykiy Bychkiv profile, running along the TD and crossing PANCAKE line, the low-velocity zones have been distinguished also.

Analysis of the published data on numerical and physical modeling, study of core of deep boreholes, as well as fault zones in natural outcrops strongly suggests to consider the low-velocity zones of the TD being ones of increased porosity, fracturing and fluid saturation. Due to the processes of fluid fracturing, mylonitization, tectonic crushing and fracturing, a secondary porosity is formed in strong crystalline and metamorphic rocks, which can be considered as a reservoirs of fluids and passways for their migration. Four small deposits of methane are known within the TD, though we can suggest its high hydrocarbon potential associated with low-velocity zones.

Acknowledgement. The study was fulfilled within the project «Geodynamics and mineral formations in sedimentary basins based on the resent geological and geophysical data. Stage I: Analysis of geophysical fields and construction of 2- and 3D geophysical models of Transcarpathian depression» (project №: II-16-20) of the National Academy of Sciences of Ukraine and partly supported by the Research grants reserved for Ukrainian researchers entitled «Tectonic architecture of northern Carpathians from geophysical and geological data» of Department of Chemistry, Life and Environmental Sustainability of University of Parma, Italy.

References

Baranova, Y.P., Yegorova, T.P., & Omelchenko, V.D. (2011). Detection of a waveguide in the basement of the northwestern shelf of the Black Sea according to the results of reinterpretation of the DSS materials of profiles 26 and 25 (in Russian). *Geofizicheskiy Zhurnal, 33*(6), 15—29. https://doi.org/10.24028/gzh.0203-3100.v33i6.2011.116790 (in Russian).

Burakhovych, T., Kushnir, A., & Ilienko, V. (2022). Modern geoelectromagnetic researches of the Ukrainian Carpathians. *Geofizicheskiy Zhurnal, 44*(3), 21—43. https://doi.org/10.24028/gj.v44i3.261966 (in Ukrainian).

Chekunov, A.V., Livanova, L.P., & Geiko, V.S. (1969). Deep structure and some features of the tectonics of the Transcarpathian trough. *Soviet Geology, 10*, 57—68 (in Russian).

Gintov, O.B. (2005). *Field tectonophysics and its application in the study of deformations of the earth's crust of Ukraine*. Kiev: Feniks, 572 p. (in Russian).

Glushko, W.W., Kruglov, S.S. (Eds.). (1971). *Geological structure and combustible minerals of the Ukrainian Carpathians*. Moscow: Nedra, 390 p. (in Russian).

Golonka, J., Gahagan, L., Krobicki, M., Marko, F., Oszczypko, N., & Slaczka, A. (2006). Plate tectonic evolution and paleogeography of the Circum-Carpathian region. In J. Golonka, F.J. Picha (Eds.), *The Carpathians and their foreland: Geology and hydrocarbon resources* (pp. 11—46). AAPG Mem. 84. https://doi.org/10.1306/985606M843066.

Golonka, J., Waśkowska, A., & Ślączka, A. (2019). The Western Outer Carpathians: origin and evolution. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 170*, 229—254.

Gurskyi, D.S., & Kruglov, S.S. (2004). *Tectonic map of Ukraine, scale 1 000 000* (in Ukrainian).

Hnylko, O.M., (2011). Tectonic zoning of the Carpathians in terms of the terrane tectonics. Section 1. Main units of the Carpathian Building. *Geodynamics,* (10), 47—57 (in Ukrainian).

Hnylko, O.M., & Generalova, L.V. (2014). Tectonic-sedimentary evolution of the Fore-Marmarosh accretionary prism of the Ukrainian Carpathians (in Russian with English summary). *Vestnik of Saint Petersburg University, Series 7, Geology, Geography*, (2), 5—23.

Ivanov, K.S. (2018). About possible maximum depth of oil deposits. News of the Ural State Mining University, (4), 41—49. https://doi.org/10.21440/2307-2091-2018-4-41-49 (in Russian).

Kolodii, V.V. (Ed.). (2004). *Carpathian Oil Province*. Lviv-Kyiv: Ukrainian Publishing Center, 388 p. (in Ukrainian).

Konečny, V., Kováč, M., Lexa, J., & Šefara, J. (2002). *Neogene evolution of the Carpatho-Pannonian region: an interplay of subduction and back-arc diapiric uprise in the mantle* (pp. 105—123). Stefan Mueller Special Publication Series.

Korchin, V.O., Burtnyi, P.O., & Karnaukhova, O.Ie. (2019). Predictive petrophysical thermobaric model of the Transcarpathian trough along the RP-17 profile. In *Geophysics and geodynamics: prediction and monitoring of geological medium* (pp. 68—70). Lviv: Rastr-7 (in Ukrainian).

Kováč, M., Plašienka, D., Soták, J., Vojtko, R., Oszczypko, N., Less, G., Ćosović, V., Fügenschuh, B., & Králiková, S. (2016). Paleogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. *Global and Planetary Change, 140*, 9—27. https://doi.org/10.1016/j.gloplacha.2016.03.007.

Kováčiková, S., Logvinov, I., Nazarevych, A., Nazarevych, L., Pek, J., Tarasov, V., & Kalenda, P. (2016). Seismic activity and deep conductivity structure of the Eastern Carpathians. *Studia Geophysica et Geodaetica, 60*, 280—296. https://doi.org/10.1007/s11200-014-0942-y.

Krobicki, M., Hnylko, O., Feldman-Olszewska, A., & Iwanczuk, J. (2014). Tectono-Stratigraphic Position of the Kaminnyi Potik Unit in the Ukrainian Carpathians and Volcanogenic Rocks of Mt Chyvchyn. In R. Rocha, J. Pais, J. Kullberg, S. Finney (Eds.), *STRATI 2013* (pp. 533—537). Springer International Publishing Switzerland. https://doi.org/10.1007/978-3-319-04364-7_102.

Kruglov, S.S. (Ed.). (1986). *Tectonics of the Ukrainian Carpathians (explanatory note to the tectonic map of the Ukrainian Carpathians scale 1:200,000)*. Kiev: Naukova Dumka, 152 p. (in Russian).

Kutas, R.I. (2021). Deep degasion and oil-and-gas containment of the Eastern (Ukrainian) Carpathians: geodynamic and geothermal aspects. *Geofizicheskiy Zhurnal, 43*(6), 23—41. https://doi.org/10.24028/gzh.v43i6.251551.

Kutas, R.I. (2014). Thermal flow and geothermic models of the Earth's crust of the Ukrainian Carpathians. *Geofizicheskiy Zhurnal, 36*(6), 3—27. https://doi.org/10.24028/gzh.0203-3100.v36i6.2014.111016.

Liashkevych, Z. (2014). Evolution and genesis of Cenozoic volcanism in Pancardia. *Bulletin of Taras Shevchenko Kyiv National University. Geology, 66*(3), 21—26.

Lozyniak, P., & Misiura, J. (2010). Main features of the geological structure of Pre-Neogene basement of the Transcarpathian deep. Evolution and genesis of Cenozoic volcanism in Pancardia. *Bulletin of Taras Shevchenko Kyiv National University. Geology, 66*(3), 21—26.

Lukin, A.E. (2014). Hydrocarbon Potential of Great Depths and Prospects of Its Development in Ukraine. *Visn. Nac. Akad. Nauk Ukr,* (5), 31—36.

Matskiv, B.V., Kovalev, Yu.V., & Pukach, B.D. (2003). *State geological map of Ukraine, scale 1: 200,000. Carpathian series. Uzhhorod group of sheets: M-34-XXIX (Snina); M-34-XXV (Uzhgorod), L-34-V (Satu Mare). Explanatory note.* Kyiv: Ministry of Ecology and Natural Resources of Ukraine, state enterprise Zahidukrgeologiya, 96 p. (in Ukrainian).

Matskiv, B.V., Pukach, B.D., Vorobkanych, V.M., Pastukhanova, S.V., & Hnylko, O.M. (2009). *State geological map of Ukraine, scale 1:200,000, sheets M-34-XXXVI (Khust), L-34-VI (Baya Mare), M-35-XXXI (Exterior), L-35-I (Visheu-De-Sous). Carpathian series. Explanatory note.* Kyiv: UkrDGRI, 188 p. (in Ukrainian).

Murovskaya, A.V. (2023). About the oil and gas potential of the Carpathian region of Ukraine. *Visn. Nac. Akad. Nauk Ukr,* (3), 52—59. doi: https://doi.org/10.15407/visn2023.03.052.

Murovskaya, A., Amashukeli, T., Yegorova, T., Bezuhlyi, R., Verpakhovska, A., & Nakapelukh, M. (2019). The main features of the lithosphere structure along the PANCAKE profile in the context of geodynamics of the Carpathian-Pannonian region. *18th International Conference on Geoinformatics —Theoretical and Applied Aspects, May 2019* (pp. 1—5). https://doi.org/10.3997/2214- 4609.201902092.

Murovskaya, A., Gintov, O., Alokhin, V., Ishkov, V., Boiarska, A., & Mychak, S. (2021). Features of the composition and deformation of rock within the Marmarosh massif (in Ukraine). *Geoinformatics, May 2021* (pp. 1—7). https://doi.org/10.3997/2214-4609.20215521082.

Murovskaya, A.V., Malytskyy, D.V., Gnyp, A.R., Makhnitskyy, N.R., Mychak, S.V., & Poliachenko, Ie.B. (2018). Active tectonics and present-day stresses in Transcarpathian trough from mechanisms of local earthquakes. *Geoinformatics, May 2018*. https://doi.org/10.3997/2214-4609.201801852.

Nakapelyukh, M., Bubniak, I., Bubniak, A., Jonckheere, R., & Ratschbacher, L. (2018). Cenozoic structural evolution, thermal history, and erosion of the Ukrainian Carpathians fold-thrust belt. *Tectonophysics, 722*, 197—209. https://doi.org/10.1016/j.tecto.2017.11.009.

Nakapelyukh, M., Bubniak, I., Yegorova, T., Murovskaya, A., Gintov, O., Shlapinskyi, V., & Vikhot, Yu. (2017). Balanced geological cross-section of the outer Ukrainian Carpathians along the PANCAKE profile. *Journal of Geodynamics, 108*, 13—25. https://doi.org// 10.1016/j.jog.2017.05.005.

Nazarevich, A.V., & Nazarevich, L.E. (2002). Deep trap-collector tectonic structures in the lithosphere of the Carpathian region of Ukraine: nature, origin and prospective resources. *Scientific Bulletin of the National Technical University of Oil and Gas, 3*(4), 10—21 (in Ukrainian).

Oszczypko, N. (2006). Late Jurassic-Miocene evolution of the Outer Carpathian fold-and-thrust belt and its foredeep basin (Western Carpathians, Poland). *Geological Quarterly, 50*(1), 169—194.

Pecskay, Z., Lexa, J., Szakacs, A., Seghedi, I., Balogh, K., Konecny, V., Zelenka, T., Kovacs, M., Poka, T., Fulpo, A., Marton, E., Panaiotu, C., & Cvetkovic, V. (2006). Geochronology of Neogene magmatism in the Carpathian arc and intra-Carpathian area. *Geologica Carpathica, 57*(6), 511—530.

Plašienka, D. (2018). Continuity and episodicity in the early Alpine tectonic evolution of the Western Carpathians: How large-scale processes are expressed by the orogenic architecture and rock record data. *Tectonics, 37*, 2029—2079. https://doi.org/10.1029/2017TC004779.

Plašienka, D., & Soták, J. (2015). Evolution of Late Cretaceous-Palaeogene synorogenic basins in the Pieniny Klippen Belt and adjacent zones (Western Carpathians, Slovakia): Tectonic controls over a growing orogenic wedge. *Annales. Societatis Geologorum Poloniae, 85*(1), 43—76.

Prykhodko, M.G., & Ponomareva, L.D. (2018). *Geological structure of the Transcarpathian depression*. Kyiv: UkrDGRI, 84 p. (in Ukrainian).

Rudko, H.I., Sobol, V.V. (2020). Prospects of oil-and-gas-bearing capacity of Ukraine at great depths for the expansion of hydro-carbon potential of Ukraine. *Mineral Resources of Ukraine*, (2), 36—42. https://doi.org/10.31996/mru.2020.2.36-42 (in Ukrainian).

Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S. Schuster, R., Tischler, M., Ustaszewski, K. (2008). The Alpine-Carpathian-Dinaridic orogenic system: correla-tion and evolution of tectonic units. *Swiss Journal of Geosciences, 101*, 139—183. https://doi.org/10.1007/s00015-008-1247-3.

Schmid, S.M., Fügenschuh, B., Kounov, A., Matenco, L., Nievergelt, P., Oberhansli, R., Pleuger, J., Schefer, S., Schuster, R., Tomljenovic, B., Ustaszewski, K., & D.J.J. van Hinsbergen (2020). Tectonic units of the Alpine collision zone between Eastern Alps and western Turkey. *Gondwana Research, 78*, 308—374. https://doi.org/10.1016/j.gr.2019.07.005.

Seghedi, I., Downes, H., Pecskay, Z., Thirlwall, M.F., Szakacs, A., Prychodko, M., & Mattey, D. (2001). Magmagenesis in a subduction-related post-collisional volcanic arc segment: the Ukrainian Carpathians. *Lithos, 57*, 237—262. https://doi.org/10.1016/S0024-4937(01)00042-1.

Sotak, J., Spisiak, J., & Biron, A. (1994). Metamorphic sequences with «Bündnerschiefer» lithology in the pre-Neogene basement of the East Slovakian Basin. *Mitteilungen der Osterreichischen Geologischen Gesellschaft, 86*, 111—120.

Starostenko, V., Janik, T., Kolomiyets, K., Czuba, W., Sroda, P., Lysynchuk, D., Grad, M., Kovács, I., Stephenson, R., Lysynchuk, D., Thybo, H., Artemieva, I.M., Omelchenko, V., Gintov, O., Kutas, R., Gryn, D., Guterch, A., Hegedűs, E., Komminaho, K., Legostaeva, O., Tiira, T., & Tolkunov, A. (2013). Seismic velocity model of the crust and upper mantle along profile PANCAKE across the Carpathians between the Pannonian Basin and the East European Craton. *Tectonophysics, 608*, 1049—1072. https://doi.org/10.1016/j.tecto.2013.07.008.

Sviridenko, V.G. (1973). Geological structure of the pre-Neogene basement of the Transcarpathian trough. *Extended abstract of candidate's thesis*. Lvov, 24 p. (in Russian).

Tretyak, K.R., Maksymchuk, V.Yu., & Kutas, R.I. (Eds.) (2015). *Modern geodynamics and geophysical fields of the Carpathians and adjacent territories*. Lviv: Publ. House of Lviv Polytechnic, 420 p. (in Ukrainian).

Verpakhovska, A., Pylypenko, V., Yegorova, T., & Murovskaya, A. (2018). Seismic image of the crust on the PANCAKE profile across the Ukrainian Carpathians from the migration method. *Journal of Geodynamics, 121*, 76—87. https://doi.org/10.1016/j.jog.2018.07.006.

Verpakhovska, O.O. (2021). Technique for the imaging crystalline basement according to the DSS data. *Geofizicheskiy Zhurnal, 43*(5), 127—149. https://doi.org/10.24028/gzh.v43i5.244076.

Verpakhovska, O., Pylypenko, V., & Chornaya, O. (2021). Features of the seismic migration method in the RomUkrSeis profile data processing. *XXth Intern. Conf. on Geoinformatics: Theoretical and Applied Aspects, Kyiv, Ukraine, 10—13 May 2021* (pp. 1—6). https://doi.org/10.3997/2214-4609.20215521058.

Yegorova, T., Verpakhovska, O., & Murovskaya, G. (2022). Three-layer structure of the Carpathian sedimentary prism from the results of seismic migration on the PANCAKE and RomUkrSeis WARR profiles. *Geofizicheskiy Zhurnal, 44*(2), 152—169. https://doi.org/10.24028/gj.v44i2.256270.

Закарпатський прогин: дослідження зон зниженої швидкості у земній корі за даними регіональних сейсмічних профілів

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Закарпатський прогин (ЗП) розташований в зоні зчленування східної окраїни терейну ALCAPA та північної частини терейну Тиса-Дакія, похованої під потужними неогеновими моласами. Структура земною кори прогину не є остаточно зрозумілою.

Мета роботи — уточнення структури земної кори ЗП, виявлення зон зниженої швидкості шляхом інтерпретації хвильового зображення, отриманого за сейсмічними даними за профілем WARR PANCAKE, з використанням методу скінченно-різницевої міграції відбитих/заломлених хвиль. За результатами інтерпретації сегмент земної кори під ЗП обмежений з південного заходу розломом, який на поверхні простежується від зони П'єнінських скель і похило занурюється у південно-західному напрямку. Виділено дві сутурні зони — П'ємонт-Лігурійську та Пенінську, які є залишками Альпійського Тетісу та поєднують Європейську плиту і мікроплиту ALCAPA, а також безкореневий фрагмент мікроплити ALCAPA. Насувний пояс Зовнішніх Карпат завглибшки до 13 км межує із ЗП по субвертикальному Закарпатському розлому. Структура земної кори Паннонського сегмента профілю інтерпретується як нагромадження товсто- і тонкошарових покривів фундаменту і чохла Тиси з накладеними молодшими структурами розтягу.

На глибинах 10—20 км виділено зону високої розшарованості та зниженої швидкості. Зона повторює малюнок ізотерм в діапазоні температур від 300 до 500 °C. На профілі ГСЗ Чоп—Великий Бичків, що проходить уздовж ЗП і перетинає профіль PANCAKE, також виділено зони зниженої швидкості. Результати чисельного та фізичного моделювання і вивчення керна глибоких свердловин, а також зон розломів у природних відслоненнях дають підстави вважати зони зниженої швидкості зонами підвищеної пористості, тріщинуватості та флюїдонасиченості. Отримані результати засвідчують високий вуглеводневий потенціал ЗП, пов'язаний із зонами зниженої швидкості.

Ключові слова: Закарпатська западина, профіль PANCAKE, профіль Чоп—Великий Бичків, скінченно-різницевий метод міграції відбиття/заломлення, зона низьких швидкостей.