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DENSITY MODEL OF THE EARTH'S CRUST IN THE JOINT ZONE OF THE OUTER CARPATHIANS AND THE EAST EUROPEAN CRATON ALONG THE CISNA – KHYRIV – RAVA-RUSKA – VELYKI MOSTY LINE

The work presents the results of 2D gravity modelling of the Earth's crust and upper mantle structure in the joint zone of the Outer Ukrainian Carpathians and the East European Craton. This study focuses on the area along the Cisna – Khyriv – Rava-Ruska – Velyki Mosty line. The profile traverses the complex border zone between Ukraine and Poland, crossing the Folded Carpathians, the Precarpathian Trough, and the Rava-Ruska zone, ultimately reaching the outer zone of the Lviv Trough. For constructing a density model, the initial structural-tectonic model of the Earth's crust was based on a deep seismic-geological cross-section along the SG-1(66) traverse of the same name. The seismic-geological data confirming the depths of the Carpathian basement and the basement surface along the seismic traverse have been verified. Additionally, the density values of both the sedimentary rocks and basement rocks have been clarified. Increased density values of the lower crust and upper mantle under the Outer Carpathians have been established. The paper examines the reflection of tectonic units in the anomalous gravity field of the Carpathian structure, specifically focusing on the Turkivskyi Paraautochthonous Complex, and deep mafic magmatic formations located between the Rava-Ruskyi and Velykomostivskyi deep faults, as indicated by seismic data. The study identifies a region of the Earth's crust between the Precarpathian and Rava-Ruskyi Faults, which probably corresponds to the Trans-European Suture Zone. This conclusion is based on the morphological features of the gravity field and the inconsistent behavior of the surfaces of the Riphean-Paleozoic basement, the pre-Riphean crystalline basement, and the Moho boundary. The modelling results confirm that the primary cause of regional negative gravity anomalies is the deepening of the Moho (and basement surface) under the Carpathians and in the Teisseyre-Tornquist Zone to 45 km (10.5 km) and 50 km (6.5 km), respectively.

Key words: Folded Carpathians, East European Craton, Trans-European Suture Zone, Teisseyre-Tornquist Zone, deep faults, Moho boundary, Bouguer gravity anomalies, gravity modelling, two-dimensional density model of the Earth's crust.

Introduction

In recent decades, numerous seismic profiles have been used to study the deep structure of the junction zone between the Outer Carpathians and the West European Paleozoic Platform (WEP), as well as the East European Craton (EEC). The area along the Ukrainian-Polish border, where the northwestern part of the Carpathians meets the WEP to the west and the EEC to the east (Fig. 1), has attracted considerable attention from researchers. Notably, the Trans-European Suture Zone (TESZ), located between these two regions, along with the Teisseyre-Tornquist Zone (TTZ) are of particular interest. Their studying has been the subject of numerous works by foreign [Alasonati Tašárová et al., 2008, 2009; Bielik et al., 2006, 2018, 2022; Dadlez et al., 2005; Grabowska et al., 2001, 2011; Grad et al., 2002, 2006, 2019; Guterch, Grad, 2006; Janik et al., 2011, 2020, 2022; Narkiewicz et al., 2015, 2017 and many others] and domestic scientists [Kutas, 2021; Makarenko, 2021; Makarenko et al., 2022, 2024; Orlyuk, 1983; Orlyuk et al., 2022, 2023; Starostenko et al., 1987; Starostenko et al., 2024a, 2004b and many others]. However, several matters regarding the deep structure and boundaries of these tectonic units, particularly in the border area between Ukraine and Poland, remain debatable. Interest in this area is also linked to the prospects for discovering new oil and gas deposits at relatively great depths, achievable by drilling.

The tectonics and geological structure of the border territory of Ukraine with Poland were studied by seismic surveys in the 1970s and 1980s at both local and regional levels. An important place in this regard is occupied by the SG-1(66) traverse, along which a seismic-geological section was constructed [Zayats, 2013]. The SG-1(66) traverse extends for 130 km in the direction of Khyriv – Mostyska – Rava-Ruska – Velyki-Mosty. It begins with the Skyba

Nappe of the Folded Carpathians, crosses the Precarpathian Trough, the Rava-Ruska Zone, and ends in the outer zone of the Lviv Trough (Fig. 1). The seismic-geological section SG-1(66) provides a detailed description of the sedimentary cover, complex geometry, and fault tectonics associated with the Riphean basement (Neoproterozoic – PR3) and the surface of the pre-Rifean basement (Meso-Paleoproterozoic – PR1+2). The most controversial issues of the deep structure of the study area include the boundaries of the tectonic units of the TESZ and TTZ, as well as the depths of the Moho surface.

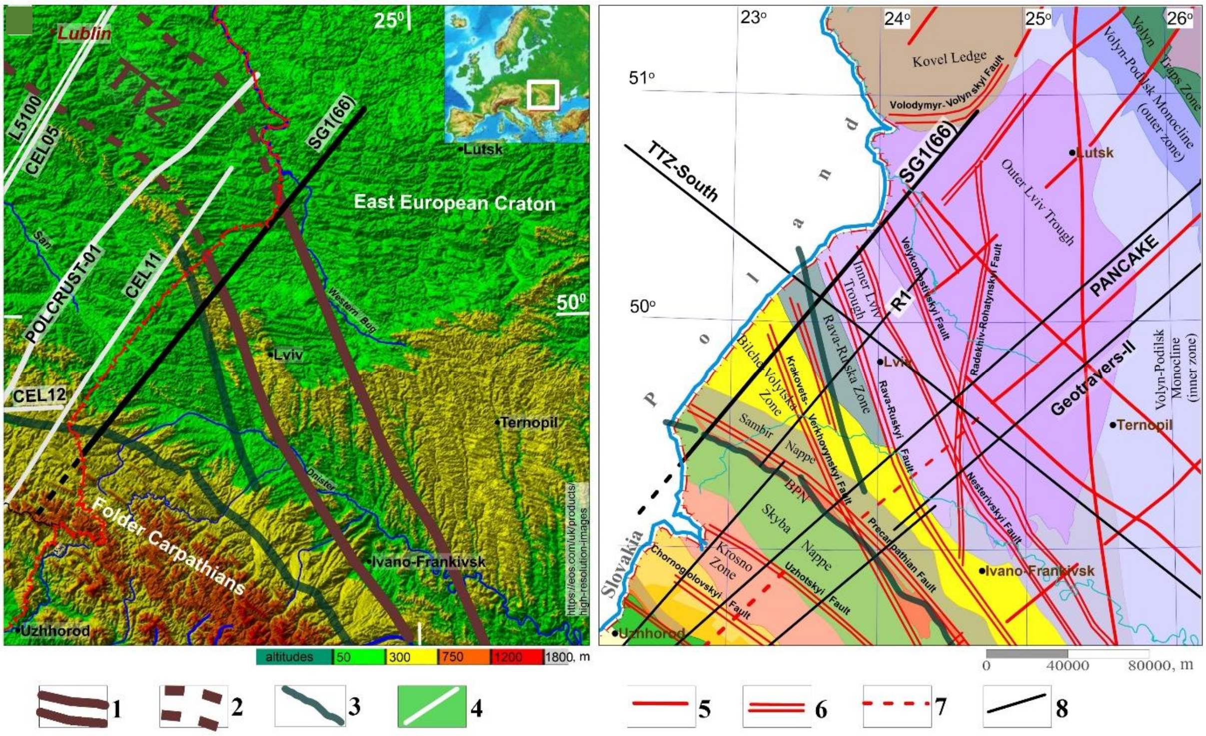

Fig. 1. Location of the SG-1(66) traverse and seismic profiles on the terrain map (a) and tectonic map fragment (b) of Western Ukraine (from [Hursky, Kruhlov, 2004], modified).

1 – TTZ boundaries based on the morphology of magnetic anomalies [Maksymchuk et al., 2024]; 2 – forecast of TTZ boundaries in Poland based on materials [Grad et al., 2002; Narkiewicz et al., 2015; Janik et al., 2022]; 3 – axis of the regional gravity minimum and its Lviv branch [Scheme…, 2002]; 4 – seismic profiles in Poland; 5 – Volyn-Podillia faults [Hursky, Kruhlov, 2004]; 6 – zones of extension of the deep faults [Zayats, 2013]; 7 – deep faults by the magnetic anomalies [Maksymchuk et al., 2023]; 8 – seismic profiles in Ukraine. The gravity modelling line is the SG1(66) profile, extended by a black dotted line. BPN – Boryslav-Pokuttya Nappe.

In eastern Poland, the Moho surface is well studied on a number of regional seismic profiles. Thus, on seismic models along the CEL05 profile, a gradual deepening of the Moho is observed from the Pannonian Basin (depths of 22–25 km), the Outer Carpathians (about 30 km) to the TESZ, TTZ (Lublin Trough) to depths reaching 50 km [Guterch et al., 2003; Grad et al., 2006]. In the seismic model based on the Poland-SPAN™ 5100 profile (near the CEL05 profile), the Moho surface under the TTZ reaches maximum depths of 50 km [Mikołajczak et al., 2018], or more than 55 km. [Mężyk et al., 2021]. A comparison of this model with the seismic-geological model POLCRUST-01 [Malinowski et al., 2013; Narkiewicz et al., 2015] indicates that in the southeast direction, closer to the border with Ukraine, the Moho depths in the TTZ zone decrease to 45–50 km. Near the border with Ukraine, in the stripe of the Carpathian regional gravity minimum, the Moho depth reaches 42 km and continues to deepen towards the Ukrainian border, as show in the CEL11 profile and Moho depth map [Janik et al., 2011]. In the seismic-geological model along the CEL12 profile, running along the Western Carpathians front, the Moho boundary monotonically deepens to 38 km as it approaches the Ukrainian border [Godová et al., 2018]. In the tectonic interpretation of the TTZ-South seismic profile in the intersection zone with the SG-1(66) traverse (Fig. 1), the Moho depth approaches 50 km [Janik et al., 2022], or even exceeds this mark [Bielik et al., 2022; Janik et al., 2020]. According to the latest map of Moho depths [Starostenko et al., 2024b], which is based on seismic data from the WARR profile network [Starostenko et al., 2024a] in western Ukraine, the Moho boundary deepens to 45 km. This finding aligns well with the definition of "thick" crust (45 km and more) for the Carpathians and the Precarpathian Trough, as noted by [Makarenko, 2021]. This suggests that the geometry of the Moho boundary is quite complex, leading to ambiguous estimates of its depths from seismic data in the area the Outer Carpathians, the WEP, and the outskirts of the EEC. The depth of the Moho boundary in the border area between Ukraine and Poland requires further comprehensive geophysical research.

In the study of the deep structure, gravity modelling is essential for determining the depths of the basement and the Moho boundary. This modelling is based on the analysis of the anomalous gravity field (Fig. 2) and the construction of density models for the geological section. Such analysis is facilitated by the availability of the high-quality Bouguer gravity field map in M 1: 200000 for Western Ukraine [Scheme…, 2002] and a network of regional seismic profiles, along which seismic-geological sections are constructed.

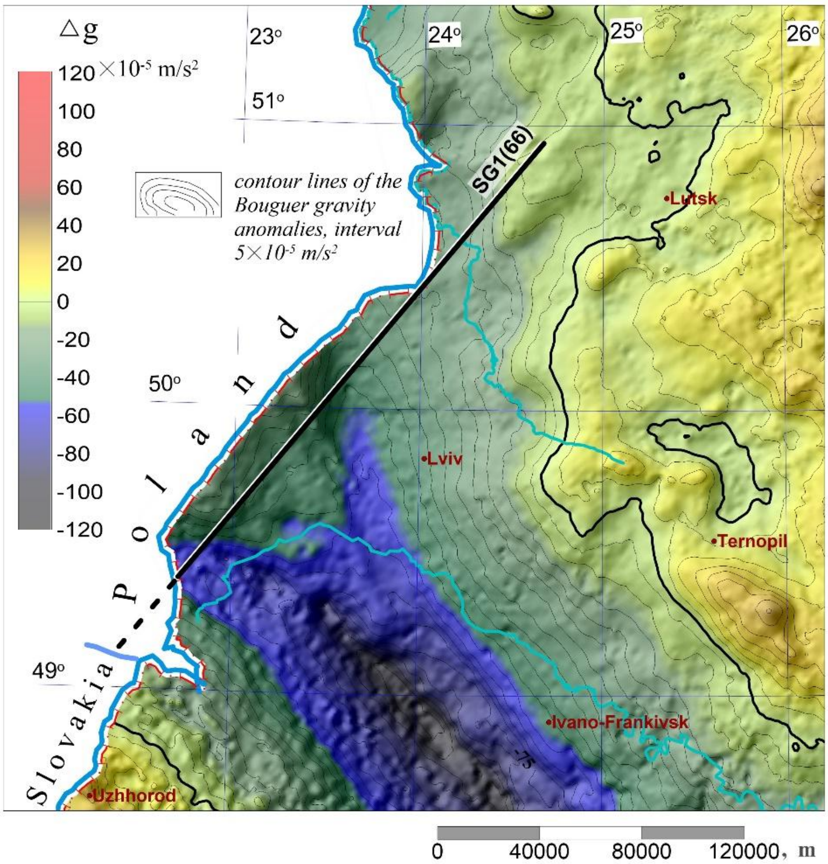

Fig. 2. Location of the modelling line (SG1(66) traverse, extended by a black dotted line) on the scheme of the Bouguer gravity field (the Western Ukrainian fragment of [Scheme…, 2002]).

The geological-tectonic nature of the anomalous gravity field of the Carpathian region has been studied in the works of many scientists (S. I. Subbotin, V. I. Starostenko, S. S. Krasovskyi, G. Yu. Boyko, S. Wybraniec, M. Bielik, T. Grabowska and others). It has been established that the regional features of the gravitational field are mainly caused by the relief of the Moho boundary, the geometry of the basement surface, the inhomogeneities of the crystalline crust, and magmatic intrusions [Subbotin, 1955; Starostenko et al., 1987; Bielik et al., 2006, Grabowska, Bojdys, 2001; Grabowska et al., 2011; Królikowski, Petecki, 2002, etc.]. The structural composition of the sedimentary cover plays a smaller role in the formation of regional anomalies, with its impact being more prominently observed in local anomalies. There are also other cases. For instance, the northeastern boundary of the Bilche-Volytska Zone in the border region of Ukraine exhibits significant, relatively localized gravity anomalies. These anomalies may result from the shallow occurrence of basement protrusions with significant amplitude. This observation is supported by the analysis of the seismic-geological model along the SG-1(66) traverse and the associated anomalous gravity field [Anikeyev & Maksymchuk, 2025]).

The aim of the work is to study the deep structure of the border region of Ukraine. This will be achieved by interpreting the Bouguer gravity field and creating a 2D density model of the Earth's crust and upper mantle along the Cisna – Khyriv – Rava-Ruska – Velyki Mosty line. The study will utilize seismic-geological sections along seismic profiles in the Ukraine-Poland border zone.

Initial data and modelling technique

The gravity modelling line starts from the Polish part of the Outer Carpathians and ends on the territory of Ukraine in the outer zone of the Lviv Paleozoic Trough of the East European Craton (Fig. 1). The initial model, which uses the results of previous modelling [Anikeyev & Maksymchuk, 2025], considers the geometry and values of the densities of the sedimentary cover, basement, and upper mantle, determined from geological and geophysical source materials.

The geometry of the initial model reproduces the sedimentary nappe, the surface of the Riphean basement K_0 and the pre-Riphean basement K_1 as seen in the seismic-geological cross-section along the SG-1(66) traverse, as well as its extrapolation to the southwest into the Outer Carpathians and the northeast into the outer zone of the Lviv Trough. This work is performed based on the seismic-geological materials presented in the monograph [Zayats, 2013].

At greater depths, the proto-basement surface K_2 and the zone of mafic magmatic formations were forecasted by the seismic-geological section along the P2 profile [Zayats, 2013] considering the geometry of K_1 and the seismic-geological section POLCRUST-01 [Narkiewicz et al., 2015]. The surface of the lower crust is designated as the conditional K_3 horizon. The K_3 horizon was traced along the geotraverse II based on the DSS data under the Boryslav-Pokuttya and Sambir Nappes, at depths of 28–31 km. In the Bilche-Volytska zone and the Lviv Trough, the K_3 horizon is found at depths ranging from 20 to 27 km [Zayats et al., 1987]. According to the density model of V. I. Starostenko [Starostenko et al., 1987] the depth of the horizon under these tectonic zones is at the level of 25–29 km. It should be noted that the K_3 horizon is absent beneath the Carpathians.

The extrapolation of the seismic-geological section was also performed taking into account the complex analysis of the morphology of the gravity field [Scheme…, 2002] (Fig. 2), the tectonic map [Hursky, Kruhlov, 2004] (Fig. 1) and the geometry of the density model along the Pancake profile [Anikeyev et al., 2022].

The geometry of the Moho boundary was forecasted considering the schemes [Bielik et al., 2018, 2022; Janik et al., 2011; Makarenko, 2021]. It also took into account depth models along the profiles CEL12 [Godová et al., 2018], TTZ-South [Janik et al., 2020, 2022], POLCRUST-01 [Narkiewicz et al., 2015], CEL11 [Janik et al., 2011], CELL05 [Guterch et al., 2003; Grad et al., 2006] and others. The analysis of Moho depth maps [Janik et al., 2011; Bielik et al., 2022; Makarenko, 2021] and the variations in gravitational field intensity [Scheme…, 2002] indicates that the Moho boundary depths likely vary between 40 and 45 km. This conclusion is based on analysis of seismic and gravity data along the Outer Carpathians and the Lviv Trough, specifically from the Precarpathian fault to the Rava-Ruskyi fault, as well as in the outer zone of the Lviv Trough, northeast of the Velykomostivskyi fault.

The densities of the initial model were determined by analyzing numerical gravity studies on of the following seismic profiles: CEL01 and CEL05 [Alasonati Tašárová et al., 2008; Grabowska et al., 2011; Šimonová, Bielik, 2016], HT-1 and VII [Dérerová et al., 2020, 2021], lithosphere models along some transects [Grinč et al., 2013], as well as the RomUkrSeis profile [Makarenko et al., 2024].

In the three-dimensional density model [Alasonati Tašárová et al., 2009], the upper, middle and lower crusts of the TESZ and EEC have densities of 2.56–2.85·10^3 kg/m^3, 2.72–2.96·10^3 kg/m^3 and 2.91–3.15·10^3 kg/m^3, respectively; the density of the upper mantle is 3.29–3.39·10^3 kg/m^3. The results of three-dimensional gravity modeling conducted by [Makarenko, 2021] reveal the density variations within the Earth's crust based on a variety of geophysical data. The findings include the following value of densities: on the surface of the basement – 2.70–2.76·10^3 kg/m^3; in the basement at a depth of 10 km – 2.75–2.82·10^3 kg/m^3; in the basement at a depth of 20 km – 2.80–2.90·10^3 kg/m^3; at a depth of 30 km – 2.90–3.02·10^3 kg/m^3; in the basement on the Moho surface – 3.05–3.15·10^3 kg/m^3.

For the initial model, we adopted the following density values: upper mantle – 3.33·10^3 kg/m^3, lower crust – 2.95–3.00·10^3 kg/m^3, middle crust – 2.88–2.90·10^3 kg/m^3, upper crust – 2.75–2.85·10^3 kg/m^3, sedimentary nappe of the Outer Carpathians and the Precarpathian Trough – 2.50–2.60·10^3 kg/m^3, sedimentary cover of the Lviv Trough – 2.55–2.70·10^3 kg/m^3.

The following selection (refinement) of model parameters by the gravity field anomalies using inverse problem-solving methods is performed in a certain sequence. In the first steps of modelling, the initial depths of the Moho boundary, the geometry of the basement blocks and their densities are refined by the large regional anomalies. Then, the geometry and densities of the upper part of the basement and sedimentary cover are corrected by the smaller regional and local anomalies.

Gravity modelling was performed applying simple selection methods, using technologies to solve a two-dimensional linear gravity direct problem. The number of interactive cycles exceeds 30; however, most of these cycles focused on detailing individual sections of the model. The parameters of the density model along the cross-section include a discretization step of 100 m along the 250 km profile. The depth has a variable discretization step: it is set at 100 m down to a depth of 5 km, then increases to 200–250 m up to 20 km, and further expands to 500–1.000 m down to 80 km. The root-mean-square deviation of the calculated final model field from the Bouguer gravity field along the profile is less than $0.25 \cdot 10^{-5}$ m/s^2. The maximum divergence of the fields up to $1.0 \cdot 10^{-5}$ m/s^2 in the contact zone of the Skyba Nappe front and Boryslav-Pokuttya Nappe is due to the increased differentiation of the physical properties of the rocks of individual sections. Also, on the border of the Bilche-Volytska and Rava-Ruska Zones, the local discrepancy is about $0.5 \cdot 10^{-5}$ m/s^2, which is due to the complex geometry of the basement surface and the influence of the Horodotskyi throw-thrust fault on the geometry of the Mesozoic-Paleozoic cover structures.

The methodological principle of gravity modelling is based on the fundamental equivalence of solving gravity inverse problems. The goal is to achieve "optimal" structural-tectonic and physical properties of the final model. The final density model should correspond to the observed gravity field with an expected error and minimally deviate (be "optimal") from the set of initial geological and geophysical materials. Both criteria are important; however, the first is more formal, while the second possesses greater physical and geological significance. The assessment of the formal accuracy of the gravity modelling is a combined process that includes both the mean square and maximum deviation. In addition, it is beneficial to analyze the reasons for any deviations between the final model field and the observed data in specific sections of the profile (area).

Results of the gravity modelling

Fig. 3 presents the resulting final density model of the deep cross-section of the Earth's crust and upper mantle in the junction zone of the Outer Carpathians and the East European Craton along the Cisna – Khyriv – Rava-Ruska – Velyki Mosty line is presented. The root-mean-square difference of the field of the final model Δg_M and the Bouguer gravity field Δg_B is $0.25 \cdot 10^{-5}$ m/s^2.

When forming regional geological models of the Carpathian cross-section, the primary task is to determine the position of deep faults that separate large blocks of the Earth's crust. All deep faults of the seismic-geological section along SG-1(66) traverse were reproduced practically unchanged. Beyond its boundaries, the location of deep faults was determined from tectonic maps [Hursky, Kruhlov, 2004; Zayats, 2013].

Geometry of the sedimentary cover and basement. The results of gravity modelling confirm the tectonic zoning of the joint zone, the geometry of the Carpathians thrust and the depths of its base (up to 10 km). They also indicate the varying depths of the basement surface in the Rava-Ruska Zone, which range from 1.5 km to 7 km, situated on the border with the Lviv Trough. Additionally, the findings corroborate the location of crustal deep faults in the seismic-geological section along the SG-1(66) traverse. Analysis comparing the morphology of the Bouguer gravity anomalies (Fig. 2) and the fault tectonics scheme [Zayats, 2013] and the seismic-geological section, the Horodotskyi throw-thrust fault is located under the northeastern border of the Bilche-Volytska Zone, just in front of the largest protrusion of the basement surface. To enhance the alignment of the model field anomalies with the local Bouguer anomalies, we provided a more detailed geometry of the individual thrusts of the flysch rocks in the Folded Carpathians, particularly in the Skyba Zone. Additionally, we slightly expanded the dimensions of the Boryslav-Pokuttya Nappe. Within the Neogene strata of the Bilche-Volytska Zone, we identified internal boundaries that likely represent the Sarmatian and Badenian stages. Furthermore, we refined the geometry of the gravitating layers within the Mesozoic-Paleozoic sedimentary cover of the Lviv Trough.

The protrusions of the surface of the Riphean basement K_0 under the front of the Sambir Nappe (next to the Mizhenetskyi fault) and at the boundary of the Bilche-Volytska and Rava-Ruska zones (next to the Horodotskyi throw-thrust fault) are distinguished by their characteristic geometry. To increase the convergence of model field anomalies with local Bouguer anomalies, the depth of the basement protrusion at the boundary of the Bilche-Volytska and Rava-Ruska Zones was reduced to 1.2 km. The surface of the crystalline basement K_1, which is practically unchanged in the model, underlies the Riphean complex and, starting from the outer zone of the Lviv Trough, dips in a southwesterly direction from a depth of 5 km to 23 km under the Outer Carpathians. The elevated surface of K_1, located between the Rava-Russkyi and Velykomostivskyi Faults at depths of 6.5–9 km, exhibits notable characteristics. Specifically, its dip relative to the surface of the Riphean basement shows sharp inconsistencies as it moves southwest from the Rava-Russkyi Fault. These features support the classification of the Rava-Russkyi Fault as a tectonic boundary of the EEC, indicating a disruption in the genetic relationship between the tectonic complications found at the boundaries of the cover and the basement. In the Outer Carpathians, a coordinated behavior of the K_0 and K_1 surfaces is restored.

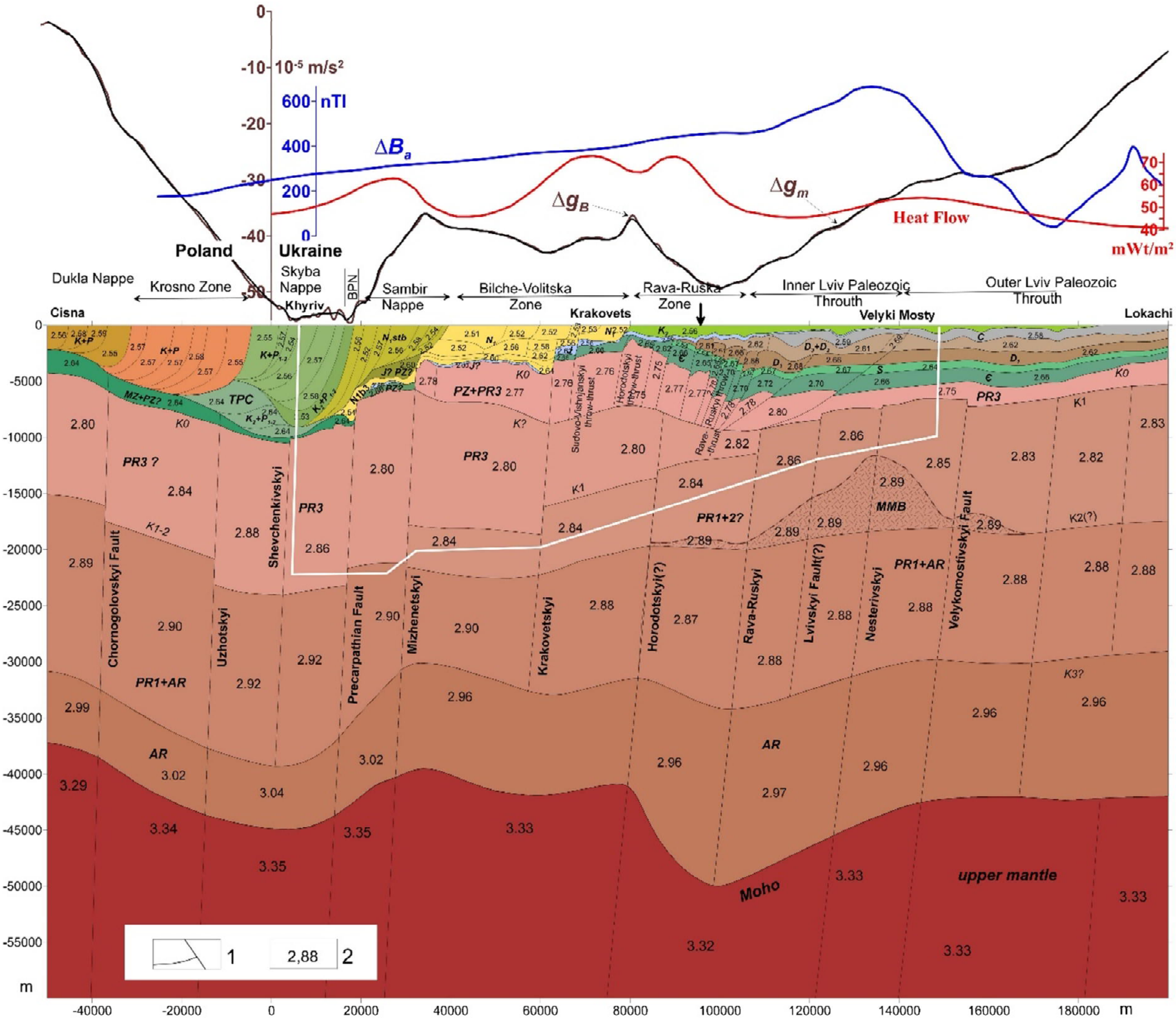

Fig. 3. Density model of the cross-section Earth's Crust and Upper Mantle along the Cisna – Khyriv – Rava-Ruska – Velyki Mosty line:

1 – density boundaries of the sedimentary cover layers and basement blocks; 2 – density of rocks, 103 kg/m^3; K_0 – surface of the folded Riphean (or Neoproterozoic and Early Paleozoic?) basement; K_1 – surface of the pre-Riphean crystalline basement; K_2 – surface of the proto-basement (within the granite layer) [Zayats, 2013]; K_3(?) – probable boundary defined as the surface of the "basalt" layer [Sollogub, et al., 1987; Zayats et al., 1987]. BPN – Boryslav-Pokuttya Nappe; TPC – Turkivskyi Paraautochthonous Complex; MMB – Mafic magmatic bodies. The white contour limits the area of the seismic-geological cross-section along the SG-1(66) traverse [Zayats, 2013]; the arrow indicates the intersection point of the modelling line with the TTZ-South seismic profile; $\Delta g_Б$ – anomalies of the Bouguer gravity field [Scheme…, 2002]; Δg_M – calculated gravity effect from density model; ΔBa – anomalous magnetic field [Map…, 2002]. Terrestrial heat flow data are taken from [Kutas, 2021].

The K_2 horizon is identified with the ancient surface of the consolidated crust in the early stages of its development. Its presence under the Outer Carpathians is not clearly defined. Its depths are approximately the same as K_1, so it is generally believed that a complex K_{1+2} boundary is recorded here. On the platform slope, according to the modelling results, the K_2 horizon occurs at depths of 16–20 km. The surface of the lower crust is predicted to lie at depths between 28 and 35 km, which could correspond to the K_3 horizon within the platform. While this horizon has not been identified under the Carpathians, it deepens to around 28–30 km under the Boryslav-Pokuttya and Sambir Nappes [Zayats, 2013], a finding that aligns well with gravity modelling results.

Densities of the sedimentary cover rocks. The averaged densities of the eastern Carpathian flysch ($2.56 \cdot 10^3$ kg/m^3), and the Outer Ukrainian Carpathians ($2.57 \cdot 10^3$ kg/m^3) as reported in studies by [Bielik et al., 2022; Makarenko et al., 2022] coincide with the averaged densities of the western Carpathian flysch, which are given in [Grinč et al., 2013].

The Dukla Nappe is characterized by slightly higher densities (2.56–2.59·10^3 kg/m^3). The Skyba Nappe and the Boryslav-Pokuttya Nappe are located within the band of low gravity field level (Fig. 2, 3). Within the Skyba Nappe, the rear parts of individual nappes are reflected by local anomalies. It is probably due to the increased density of cores of the folds filled with Cretaceous deposits. Relatively less dense rocks of the Boryslav-Pokuttya Nappe and the southwestern part of the Sambir Nappe (2.52–2.53·10^3 kg/m^3) cause negative local anomalies. In the Bilche-Volytska Zone, with depth (> 3 km), the density of the Neogene stratum increases to 2.60–2.64·10^3 kg/m^3. In the Lviv Paleozoic Trough, densities increase with depth from 2.56–2.58·10^3 kg/m^3 (Mesozoic sediments) to 2.66–2.72·10^3 kg/m^3 (Cambrian strata).

The density of rocks in the crystalline part of the Earth's crust. According to the results of gravity modelling, the crustal rocks under the Outer Carpathians and the Sambir Nappe are compacted. In particular, the density of the lower crust reaches 2.99–3.04·10^3 kg/m^3, which in this part of the section is close to the density at the Moho boundary according to [Makarenko, 2021; Starostenko et al., 2024b] and [Šimonová, Bielik, 2016]. The densities of the upper crust (2.75–2.78·10^3 kg/m^3) and the lower crust (2.96–2.97·10^3 kg/m^3) from the Bilche-Volytska Zone to the EEC coincide with the averaged densities of the corresponding parts of the lithosphere models along a number of transects presented in [Grinč et al., 2013]. The densities of the basement in the final model generally align well with the density distribution schemes observed on the basement surface and at depths of 10, 20, and 30 km within the Earth's crust, as reported by [Makarenko, 2021]. This agreement holds true along the modelling line.

The density of upper mantle. Under the Folded Carpathians, according to the results of gravity modelling, the density of the upper mantle was determined to be within 3.34–3.35·10^3 kg/m^3. In the TTZ zone under the Moho depth of up to 50 km, which was determined considering the works [Starostenko et al., 2024a, 2024b], the mantle density was reduced to 3.32 10^3 kg/m^3. We do not exclude that the Moho depth in this zone could be greater. Thus, the work [Guterch, Grad, 2006] notes the probability of an increase in Moho depths to 55 km within the TTZ in southern Poland. An increase in the depth of the Moho boundary under the TTZ in the density model will lead to an increase in the density of the upper mantle and lower crust.

Table presents the generalized results of gravity modelling of the Earth's crust cross-section along the Cisna – Khyriv – Rava-Ruska – Velyki Mosty line.

Summary of the results of gravity modelling of the Earth's crust section along the Cisna – Khyriv – Rava-Ruska – Velyki Mosty line: depths, km, and densities, 10^3 kg/m^3, of the main tectonic units

Tectonic units	Sedimentary cover (above K_0)/ depths / densities	Upper crust (K_0 – K_{1+2})/ depths / densities	Middle crust (K_2 – K_3)/ depths / densities	Lower crust (K_3 – Moho)/ depths / densities	Upper mantle / densities
OUC	0–8 / 2.55–2.58	10–24 / 2.80–2.88	15–38 / 2.89–2.92	31–45 / 2.99–3.04	3.29–3.35
TPC	4.7–10 / 2.64	–	–	–	–
BPN	0–9 / 2.53	–	–	–	–
SN	0–9 / 2.52–2.60	5.7–23.7 / 2.80–2.86	21.5–39 / 2.90–2.92	30–45 / 2.90–3.04	3.35
BVZ	0–4.3 2.51–2.62	3.1–22.4 / 2.76–2.84	21.5–33 / 2.88–2.90	30–42 / 2.96	3.33
RRZ	0–6.8 / 2.56–2.70	1.3–9.3 / 2.75–2.84	20–34 / 2.87–2.88	31.5–50 / 2.96–2.97	3.32
LT(inner)	0–6.8 / 2.56–2.72	5.5–20 / 2.78–2.86	18.3–34 / 2.88	30.5–50 / 2.96–2.97	3.33
MMB	–	11.5–20 / 2.89	–	–	–
LT(outer)	0–5.7 / 2.56–2.66	3–18.5 / 2.75–2.89	18–30 / 2.88	30–42.3 / 2.96	3.33

OUC – Outer Ukrainian Carpathians (except BPN); TPC – Turkivskyi Paraautochthonous Complex; BPN – Boryslav-Pokuttya Nappe; SN – Sambir Nappe; BVZ – Bilche-Volytska Zone; RRZ – Rava-Ruska Zone; LPT(inner) – Lviv Paleozoic Trough (inner zone); MMB – mafic magmatic bodies; LPT(outer) – Lviv Paleozoic Trough (outer zone).

Tectonic interpretation of the density model

The tectonic interpretation of the constructed density model (Fig. 4) was performed considering the available data on the deep geological structure and tectonics of the research region. The geological and tectonic complexes that are reflected in the gravity anomalies include the following.

Mesozoic-Paleozoic complex of sedimentary strata and basement under the Carpathian thrust. In the density model under the Carpathian thrust, autochthonous Mesozoic (Mesozoic-Paleozoic?) strata, as in the seismic-geological cross-section along SG-1(66) transect, lie on the Proterozoic (Paleozoic-Proterozoic?) basement and are in places covered by Neogene rocks of small thickness. The occurrence of autochthonous Mesozoic sediments of carbonate and non-flysch terrigenous rocks under the Sambir Nappe and the Folded Carpathians is indicated, for example, by geodensity models along a number of regional profiles [Mayevsky et al., 2012] and geological interpretations of the complex of seismic materials along profiles P1, P2 [Zayats, 2013].

The Turkivskyi Paraautochthonous Complex (TPC) of Paleogene-Cretaceous sediments is distinguished in the area of maximum dipping of the basement under the Outer Carpathians, above which the Krosno Zone front borders the Skyba Nappe. The TPC, up to 30 km wide, has a significant spread with a gradual increase in the depth of occurrence in the southeast direction from the border territory of Poland along the strike of the Skyba Nappe. This closed structural object was formed as a result of gravitational sliding in the autochthonous surface along the Uzhotskyi scarp into the northeastern part of the depression at the first stages of the formation of flysch folds. Its structural and tectonic isolation and location above the Uzhotskyi Fault zone create favorable conditions for migration and retention of deep hydrocarbons in large volumes [Zayats, 2013]. Gravity modelling confirmed the presence and size of the TPC with a weighted average density of $2.64 \cdot 10^3$ kg/m^3.

TESZ, TTZ. In the gravity field along the modelling line, the tectonic blocks of the Sambir Nappe, Bilche-Volytska and Rava-Ruska Zones stand out in quite contrasting ways. In many works, this area is considered as TESZ. It is separated from the Folded Carpathians by the Precarpathian Fault, and from the EEC by the Rava-Ruskyi Fault. We interpreted the modelling results considering the analysis of the content of these tectonic units given in the works [Grad, 2019; Narkiewicz et al., 2015].

In Ukraine, within the southwestern margin of the EEC, between the Rava-Russkyi and Velykomostivskyi deep faults, a TTZ is predicted along a strip of intense positive magnetic anomalies, which here has a width of 30–50 km [Maksymchuk et al., 2024]. A series of basement faults is between these deep faults (Nesterivskyi, Lvivskyi, and probably others).

In Poland, the EEC is limited by the subvertical Tomaszów Fault, the strike zone of which corresponds to the TTZ. In the southeast, in Ukraine, the TTZ has a continuation by the Rava-Ruskyi Fault zone [Narkiewicz et al., 2015; 2017]. According to the results of gravimagnetic modelling [Grabowska, Bojdys, 2001], a deep fault has also been identified that delimiting the TTZ on SW. We can conclude that, the Rava-Ruskyi Fault, which continues from the Tomaszów Fault from Poland to Ukraine, marks the southwestern boundary of the TTZ – the Teisseyre-Tornquist Line (TTL) [Grad, 2019; Narkiewicz et al., 2015].

The TESZ, which contacts the TTZ in the northeast [Dadlez et al., 2005; Narkiewicz et al., 2015], is considered to be a much more complex zone than a separate suture, formed during the evolution of the crust from a complex collage of terranes during the late Paleozoic [Pharaoh, et al., 1999]. By definition [Narkiewicz et al., 2015], the TESZ is a transitional structure between the WEP and the EEC, consisting of subordinate tectonic blocks (terranes) of different ages with fault contacts, which probably represent (at least partially) accretionary sutures.

In the work [Zayats et al., 1987], which analyzed seismic data from the DSS, CDPM and drilling, it was suggested that on the territory of Ukraine, the southwestern edge of the EEC is bordered by Caledonian (early Paleozoic) folded structures. The characteristics described support the hypothesis that the Earth's crust in the area between the Folded Carpathians and the southwestern edge of the EEC corresponds to the TESZ. This aligns well with the tectonic schemes proposed by [Guterch, Grad, 2006] and [Narkiewicz, Petecki, 2017], which encompass the border region of Ukraine.

A certain correlation with the gravity field along the modelling line is observed with the thermal field. The Sambir Nappe, significant parts of the Bilche-Volytska and Rava-Ruska Zones are distinguished by anomalies of high Heat Flowes, reaching 60–70 mW/m^2 [Kutas, 2021]. The maximum values of the thermal field tend to the zones of Mizhenetskyi, Krakovetskyi and Horodotskyi deep faults. An increase in heat flux is also observed in the Lviv Paleozoic Trough between the Rava-Ruskyi and Velykomostivskyi deep faults (Fig. 4).

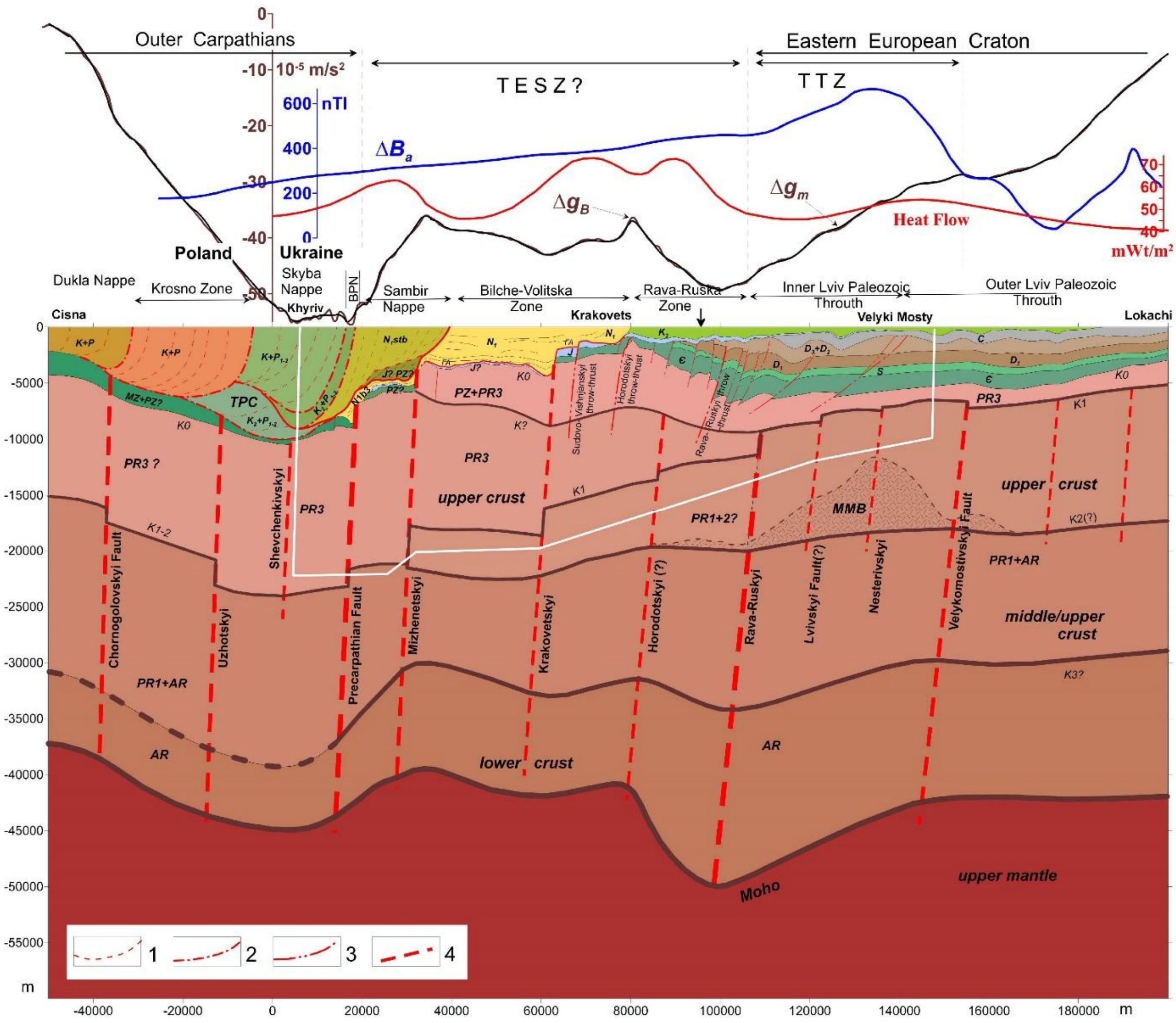

Fig. 4. Tectonic interpretation of the Density model along the Cisna – Khyriv – Rava-Ruska – Velyki Mosty line:

1 – boundaries of lithological-tectonic nappes; 2 – sole of the nappes; 3 – throw-thrust faults in the Paleozoic; 4 – deep faults. EEC – East European Craton; TTZ – Teisseyre-Tornquist Zone; TESZ – Trans-European Suture Zone. Other explanations as in Fig. 3.

Zone of development of mafic magmatic formations. A zone of development of mafic magmatic bodies was identified according to seismic materials [Zayats, 2013] in the southwest of the EEC between the surface of the protobasement K_2 and the pre-Riphean surface K_1, along a series of traverses P5, SG-1(67), P3, P2. A deep zone of compacted up to $2.89{\cdot}10^3$ kg/m^3 mafic magmatic bodies was distinguished in the density model, between the Rava-Ruskyi and Velykomostivskyi Faults.

The same mafic bodies are also traced in Poland in seismic-geological sections along the POLCRUST-01 profiles [Malinowski et al., 2013; Narkiewicz et al., 2015], PolandSPAN™ L5100 and L5200 [Mężyk et al., 2021] and in the results of gravimagnetic modelling of the SG-1(67) profile [Anikeyev et al., 2019]. In the section, this zone is associated with a number of deep faults of the EEC margin and in plan coincides with the extension of the TTZ. The zone is likely to contain "intrusive bodies that penetrated Proterozoic sediments. Uplifts of the K_2, K_1 horizons are observed above this zone. The blocks separated by faults are inherited by the sedimentary cover in the form of southwest-dipping fault-thrust planes. The intrusions could penetrate along the faults of the granite layer and play a structure-forming role in the sedimentary cover" [Zayats, 2013]. In the magnetic field, they are reflected by a large positive anomaly (Fig. 4), the nature of which is associated with highly magnetized deep bodies of mafic-ultramafic composition [Pashkevich et al., 2025].

Depths of the Moho boundary. In the density model, the depths of the Moho boundary along the modelling line vary from 37 km to 50 km. The depth of the Moho boundary gradually increases from the Folded Carpathians (Dukla Nappe, 37 km) towards the EEC (42 km). In some areas, the maximum Moho depths were found as follows: 45 km under the Skyba Nappe and 50 km under the TTZ (Rava-Ruskyi Fault). In the area where the modelling line intersects with the TTZ-South seismic profile [Janik et al., 2022] the Moho boundary at depths from 45–48 km to 50 km (Fig. 4), and it may be even deeper. This suggestion arises from the detection of an anomalous zone of velocity reduction, dipping to 8.10 km/s below the Moho boundary as defined in this interpretation. Previous interpretations of this profile [Janik et al., 2020] indicate a clear deepening of the Moho boundary to 50 km, with similar dimensions noted. Furthermore, there is an uplift of the middle crust surface to depths of 12–15 km and the lower crust to 32–34 km. In our density model, these surfaces in the area of intersection with the TTZ-South profile were also found at the same depths.

Conclusions

A density model of the Earth's crust has been developed along the Cisna – Khyriv – Mostyska – Rava-Ruska – Velyki Mosty line in the junction zone of the Outer Carpathians and the East European Craton. This model accurately represents the seismic-geological section along the SG-1(66) traverse, detailing the structure of the sedimentary cover, the fault-block architecture of the basement of the Outer Carpathians and the south-western slope of the East European Craton.

The main findings from gravity modelling are as follows.

The Mesozoic-Paleozoic complex under the Carpathian Thrust and under the Bilche-Volytska Zone of the Precarpathian Trough is outlined. The deep Turkivskyi Paraautochthonous Complex of Paleogene-Cretaceous sediments with increased density is distinguished under the boundary between the Krosno and Skyba Zones. Under the Folded Carpathians, an increased density of rocks of the lower crust and upper mantle up to $3.04 \cdot 10^3$ kg/m^3 and $3.35 \cdot 10^3$ kg/m^3, respectively, is established.

Based on the morphological characteristics of the gravity field and the inconsistent behavior of the surfaces of the Riphean-Paleozoic basement, the pre-Riphean crystalline basement, and the Moho boundary, a region of the Earth's crust has been identified between the Precarpathian and Rava-Ruskyi Faults. This region likely corresponds to the Trans-European Suture Zone.

Within the Teisseyre-Tornquist zone, between the Rava-Russkyi and Velikomostivskyi faults, a deep area of development of compacted mafic magmatic formations has been identified.

The depth of the Moho boundary has been forecasted. Its characteristic feature is significant variations in the depth of occurrence from 37 to 50 km in the junction zone of the Outer Carpathians and the East European Craton. Based on regional negative gravity anomalies under the Folded Carpathians and the Teisseyre-Tornquist zone, the Moho boundary is predicted to deepen to 45 and 50 km, respectively.

The deep Turkivskyi Paraautochthonous Complex as well as Paleozoic deposits, which is situated in an area characterized by the development of throw-thrust faults within the inner zone of the Lviv Trough, and possibly in the Rava-Ruska Zone, should be regarded as a promising objects for the exploration of new oil and gas fields.

The obtained results confirm the high informativeness of gravity modeling for studying the deep structure of the Earth's crust and upper mantle. It is advisable to construct density models along other existing seismic-geological sections in the border areas of Ukraine and Poland, which would allow obtaining new data on the tectonic structure of the transition zone from the Outer Carpathians to the East European Craton.

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ГУСТИННА МОДЕЛЬ ЗЕМНОЇ КОРИ ЗОНИ ЗЧЛЕНУВАННЯ ЗОВНІШНІХ КАРПАТ ТА СХІДНОЄВРОПЕЙСЬКОЇ ПЛАТФОРМИ УЗДОВЖ ЛІНІЇ ТІСНА – ХИРІВ – РАВА-РУСЬКА – ВЕЛИКІ МОСТИ

Наведено результати гравітаційного 2D-моделювання будови земної кори та верхньої мантії в зоні зчленування Зовнішніх Українських Карпат та Східноєвропейської платформи вздовж лінії Тісна – Хирів – Рава-Руська – Великі Мости. Профіль проходить через складнопобудовану зону прикордоння України і Польщі, перетинає Складчасті Карпати, Передкарпатський прогин, Рава-Руську зону та закінчується у зовнішній зоні Львівського прогину. Для побудови густинної моделі як вихідну структурно-тектонічну модель земної кори використано глибинний сейсмогеологічний розріз по однойменному траверсу СГ-1(66). Підтверджено сейсмогеологічні дані щодо глибин карпатської основи та поверхні фундаменту уздовж сейсмогеотраверсу. Уточнено значення густин порід осадового комплексу та фундаменту. Встановлено підвищені значення густини нижньої кори та верхньої мантії під Зовнішніми Карпатами. Досліджено відображення у аномальному гравітаційному полі тектонічних одиниць Карпатської споруди, Турківського параавтохтонного комплексу, глибинних мафічних магматичних утворень поміж Рава-Руським та Великомостівським глибинними розломами, виділених за сейсмічними матеріалами. На основі морфологічних особливостей гравітаційного поля та неузгодженої поведінки поверхні рифей-палеозойського фундаменту, поверхні дорифейського кристалічного фундаменту та межі Мохо, між Передкарпатським та Рава-Руським глибинними розломами виокремлено ділянку земної кори, яка, ймовірно, відповідає Транс'європейській шовній зоні. Моделюванням підтверджено, що основною причиною регіональних від'ємних гравітаційних аномалій є заглиблення Мохо (та поверхні фундаменту) під Карпатами та у зоні Тейссейре – Торнквіста до 45 км (10,5 км) та 50 км (6,5 км) відповідно.

Ключові слова: Складчасті Карпати, Західноєвропейська платформа, Східноєвропейська платформа, Транс'європейська шовна зона, зона Тейссейре – Торнквіста, глибинні розломи, межа Мохо, аномалії поля сили тяжіння, гравітаційне моделювання, двовимірна густинна модель земної кори.

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