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DENSITY MODEL OF THE EARTH CRUST OF THE UKRAINIAN CARPATHIANS ALONG THE PANCAKE PROFILE

The purpose of the work is the analysis and geological-tectonic interpretation of the anomalous gravity field of the Ukrainian Carpathians and adjacent territories, as well as the construction of a density model of the Earth's crust and upper mantle according to the international PANCAKE seismic profile. The need to build a density model along the PANCAKE profile is due to the significant interest of a number of geologists and geophysicists in the results of seismic research along this profile. It is also caused by certain discrepancies in the seismological models of different authors. The gravity modeling technique, used in the work, includes the analysis of geological-geophysical maps and models. They are related to the geological-tectonic structure of the research region, to the creation of the initial structural part of the model and to the determination of the densities of strata and blocks of the model. The geometry and densities of the model are refined by the selection method, which is based on the interactive solution of the direct problem of gravimetric and the analysis of the reasons for the inconsistency of the calculated gravity field and Bouguer anomalies. A qualitative correspondence of the density model to the tectonic interpretation of the seismic section along the PANCAKE profile was achieved by using the methods of gravity modeling. The modelling results confirm the four-layer structure of the Earth's crust: the sedimentary cover, the upper, middle, and lower parts of the crust, which differ significantly in density. There is also evidence of the difference of the ALCAPA lithospheric plate, Flysch Carpathians and Precambrian Craton in Earth's crust and upper mantle structure. The ALCAPA plate is characterized by a small thickness (up to 29 km) and a low density of the Earth's crust. The density of the ALCAPA upper mantle is lower (3.20–3.21$\times$10^3 kg/m^3) compared to the upper mantle under the Ukrainian Carpathians and the East European Craton (3.28–3.30$\times$10^3 kg/m^3). This may be related to a change of a mantle composition and increased heat flow under ALCAPA. The Ukrainian fragment of the East European craton in the PANCAKE profile zone is characterized by a typical thickness of the crust (~41–45 km). The upper part of the crystalline crust, in contrast to the middle (2.86–2.90$\times$10^3 kg/m^3) and the lower part (2.98–3.10$\times$10^3 kg/m^3), is characterized by a lower density and greater differentiation in horizontal direction and with depth (from 2.66$\times$10^3 kg/m^3 to 2.86$\times$10^3 kg/m^3). The complex transition zone (subduction zone, Carpathian Orogen) between the ALCAPA microplate and the East European Craton causes an intense negative Bouguer anomaly – the Carpathian gravity minimum, which reaches –90$\times$10^{-5} m/s^2. It has a complex nature: Neogene and Paleogene-Cretaceous flysch rocks low density ($\leq$2.50$\times$10^3 kg/m^3) of the Boryslav-Pokuttia cover, the main huge Precarpathian sub-vertical fault (>4 km) on the extreme southwestern slope of the platform (relatively local factors) and significant deepening of the MOHO surface under the Carpathian structure (regional factor). According to our density model, the depth of the MOHO under the front of the Carpathian thrust reaches 56 km.

Key words: Ukrainian Carpathians; Earth’s crust; upper mantle; Moho surface; Bouguer gravity anomalies; seismic model; gravity modelling; density model.

Introduction

The construction of density models, as a result of the interpretation of Bouguer gravity anomalies, is an important stage in the creation of integral geological and geophysical models of the Earth's crust.

Special attention to geological and geophysical research in the territory of the Ukrainian Carpathians is due to the urgent need to expand the energy resource base of Ukraine and the high prospect of discovering new deep oil and gas deposits in the under-thrust Carpathians [Zayats, 2013; Mayevsky et al., 2012; Monchak & Anikeyev, 2022, etc.].

On the PANCAKE international profile (650 km long) (Fig. 1) seismic surveys by the method of wide-angle deep seismic sounding (WDSS) were conducted in 2008. The PANCAKE profile begins in the central part of the Pannonian Basin in Hungary, passes through the Ukrainian part of the Eastern Carpathians and southwestern slope of the East European Platform and ends on the beginning of the Ukrainian Shield (Fig. 2). Performed seismic studies along the

PANCAKE profile made it possible to build deep velocity models of the Earth's crust and upper mantle [Starostenko et al., 2013]. Based on the results of these works, the relief of the basement and the Mohorovičić discontinuity (usually referred to as the MOHO) was studied along the entire profile. Within the Pannonian basin, the thickness of the Earth's crust together with the sedimentary layer is 22–23 km. The upper part of the basement, which is composed of rocks of probably Paleozoic age, is located at a depth of about 8 km and rises to a depth 3–4 km in the Transcarpathian Trough. In the northeastern direction, the thickness of the Earth's crust increases sharply, reaching maximum depths under the southwestern part of the Precarpathian Trough. On the slope of the East European platform, the basement lies at depths of up to 4 km (Lviv Paleozoic Trough). It is interesting that according to the results of these studies under the Ukrainian Carpathians, no pronounced roots of the Earth's crust were found. It was the case in the works using the methods of deep seismic sounding (DSS) and the correlation method of refracted waves (CMRW) along Geotraverse II [Sollogub et al., 1987, 1993; Zayats et al., 1987; Zayats, 2013]. The MOHO boundary is predicted here at depths of 45–55 km. Further seismic constructions along the PANCAKE profile [Verpakhovska et al., 2018] using the WARR (wide-angle reflection and refraction) data migration method confirmed the obtained results [Starostenko et al., 2013] related to the depth of the MOHO zone. However, certain differences were found in the structure of the upper part (up to 22 km) of the Earth's crust.

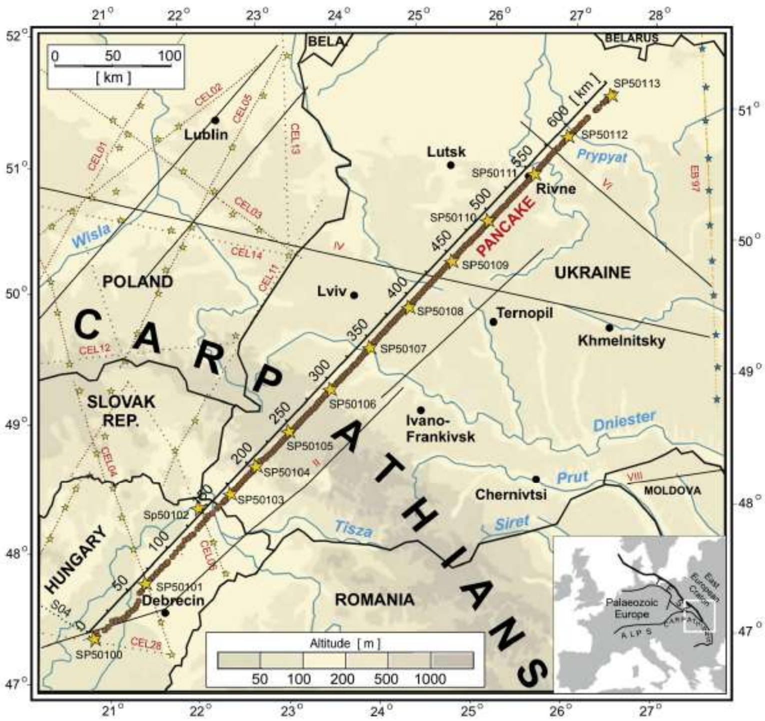

Fig. 1. Location of the main regional seismic profiles and the PANCAKE profile in the studied territory (after Starostenko et al., 2013)

Stars represent the shot points and red-yellow dots represent recording stations of WARR CELEBRATION 2000 and of PANCAKE profiles; black lines represent older profiles. Inset map shows the location of the target area in Europe

Elimination of the mentioned discrepancies in seismic-geological models in the area of the Folded Carpathians can be achieved by involving additional geophysical materials. For example, additional information about the structure and material composition of the crust can be obtained from the results of the interpretation of Bouguer gravity anomalies and the construction of a density model of the Earth's crust. The presence of a depth seismological section along the PANCAKE profile, as well as detailed maps of the gravity field for western Ukraine, open up opportunities for building a density model, consistent with the geometry of the seismic section and with the distribution of seismic wave velocities with depth.

By the density model of the structure of the Earth's crust and upper mantle, we understand their approximation by a set of geological bodies limited by surfaces and faults with their inherent density characteristics, the total gravitational effect of which corresponds to the Bouguer anomalies observed along an earth's surface.

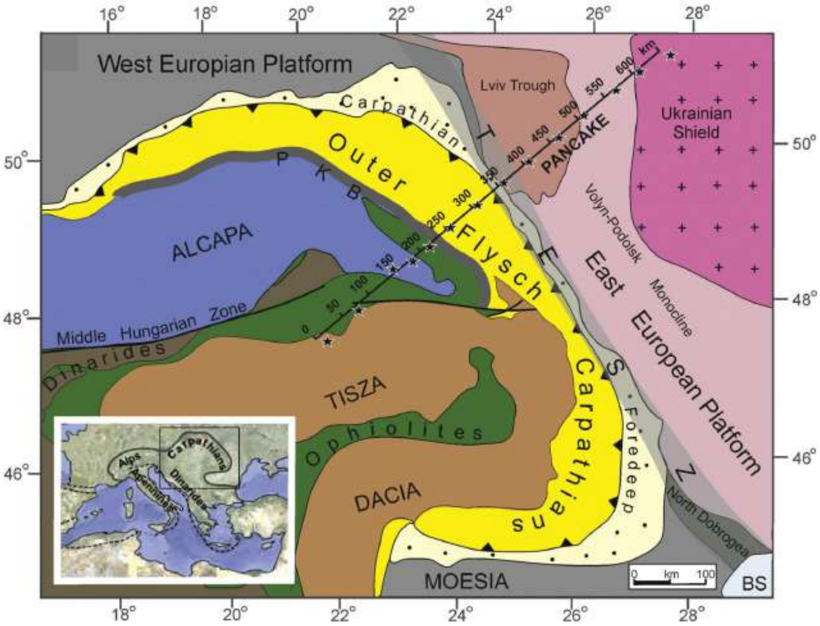

Fig. 2. Tectonic map for the Carpathian-Pannonian system with location of the PANCAKE profile (after Verpakhovska et al., 2018; Schmid et al., 2008, Gągała et al., 2012)

Inset map shows the Alpine-Mediterranean Belt with the location of study area (rectangle). BS – Black Sea, PKB – Pieniny Klippen Belt, TESZ – Trans-European Suture Zone. Stars denote the shot points (SP) on the PANCAKE profile

Density models are based on the analysis and interpretation of gravity field anomalies, taking into account the data of other geophysical methods of geological environment research. The methods of density models building are based on algorithms for solving direct and inverse gravimetry problems.

The methods of research the distribution of rocks with depth based on the results of the interpretation of the anomalous gravity field and the construction of density models of the geological environment were actively developed in Ukraine in the 70s and 90s of the last century by E. H. Bulakh, G. Ya. Golizdra, S. S. Krasovsky, V. I. Starostenko and others.

The use of gravimetry in combination with seismic exploration significantly increases the reliability of building complex geological-geophysical models, which is important both when studying the nature of deep inhomogeneities in the Earth's crust and when solving applied problems of geophysics. In particular, in a recent work [Besutiu et al., 2021], a spatial model of the branched canal system of the Ciomadul volcano was obtained due to the use of high-precision gravimetric data. The Ciomadul volcano is located in the inner part of the East Carpathians bend zone on the territory of Romania.

Examples of the high efficiency of complex interpretation of geophysical materials with using gravimetric data are the works [Tašárová et al., 2009, 2016, Grabowska et al., 2011, Godová et al., 2021, etc.], which present density models of the Carpathian-Pannonian basin structure lithosphere along a series of CELEBRATION 2000 profiles (see Fig. 1). Density models were constructed by gravity modelling using seismic models and other geophysical data. Gravity modelling is also effective in studying the structure and geodynamics of seismically active zones of the Carpathians [Besutiu et al., 2018].

The need to build a density model along the PANCAKE profile is due to the fact that the results of seismic research on this profile [Starostenko et al., 2013; Verpakhovska et al., 2018] caused considerable interest in the wide circles of geologists and geophysicists, as well as in connection with certain discrepancies in the seismological models of different authors.

Therefore, the purpose of the work is the analysis and geological-tectonic interpretation of the anomalous gravity field of the Ukrainian Carpathians and the adjacent troughs, the construction of a density model of the Earth's crust and the clarification of the deep structure along the PANCAKE profile.

General features of the geological and tectonic structure reflection of the region in the gravity field anomalies

To analyze the anomalous gravity field (Bouguer gravity) of the Ukrainian Carpathians, we used the latest maps of the Western regions of Ukraine gravity field [Scheme of the gravity field of Ukraine, 2002; Bilichenko, 1999].

The anomalous gravity field of the Ukrainian Carpathians and adjacent territories is characterized by significant differentiation and contrast. Its main feature is the characteristic regional negative Carpathian gravity minimum (~$100 \cdot 10^{-5}$ m/s^2) in the frontal part of the Outer Ukrainian Carpathians, as well as the linear extension of iso-anomalies with a gradual increase of the field to a positive level in the Lviv Trough and the mosaic nature of gravity anomalies on the Ukrainian Shield.

In general, the morphology, direction of extension, dimensions, and intensity of gravity field anomalies reflect the structure of the sedimentary cover, fault tectonics, complications of the basement surface and the MOHO boundary, as well as density inhomogeneities in the Earth's crust and in the substrate of the upper mantle.

The PANCAKE profile from the Pannonian Basin enters the Inner and Outer Ukrainian Carpathians (IUC and OUC), crosses the Precarpathian Trough, the Volyn-Podilsk margin of the East European Craton (EEC) and reaches the Volyn-Polysky Volcanic-Plutonic Belt on the Ukrainian Shield (USh) (Fig. 3 and see Fig. 2).

The Transcarpathian trough stands out due to the high spatial contrast of gravity field anomalies (positive level of Bouguer gravity anomalies). The Ukrainian Flysch Carpathians are characterized by almost linear, northwesterly trending anomalous zones (negative level of Bouguer anomalies) and regional Carpathian gravity minimum (in the frontal part of the OUC). Within the slope of the EEC, a linear extension of iso-anomalies with a gradual growth of the field to a positive level is partially preserved (zero isoanomaly between the inner and outer zones of the Lviv Trough); the intensity of large mosaic anomalies increases up to and including the USh (Fig. 4).

Below we will focus on the main tectonic units along the PANCAKE profile, which have characteristic features in the Bouguer gravity anomalies. These signs are often more clearly visible in local anomalies, gradient bands (Fig. 5), isolated by the transformation: the gravity field minus the result of its averaging. Methods of transformation and anomalous field components analysis are given in [Anikeyev, Maksymchuk & Pylyp'yak, 2019].

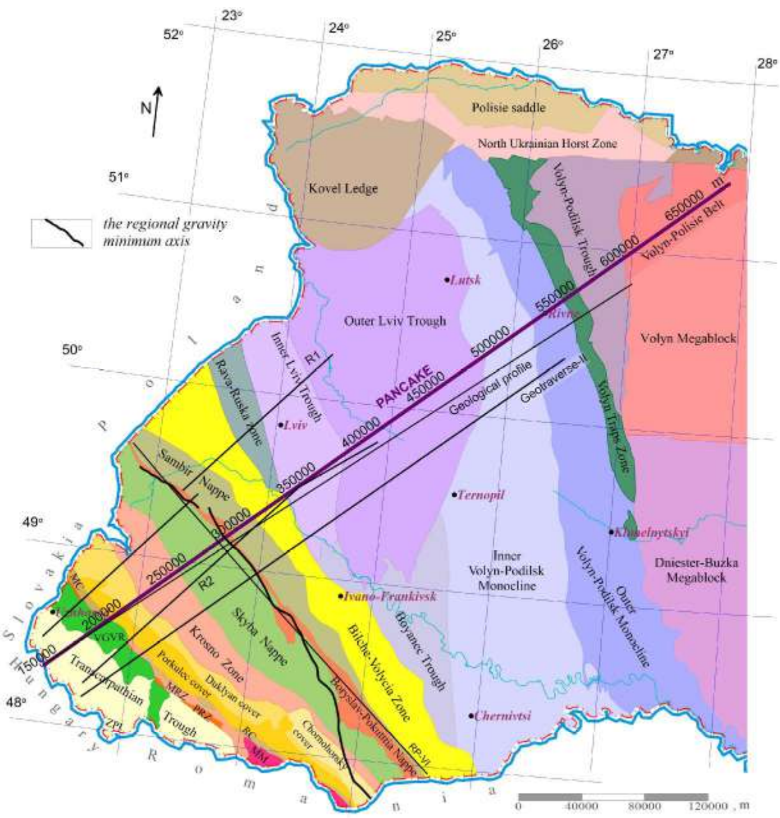

Fig. 3. Location of the PANCAKE profile and regional seismic profiles on the tectonic map of Ukraine (the western fragment modified after the Tectonic Map of Ukraine, 2004)

Tectonic zones: ZPI – Pannonian intermountain zone; MC – Magury cover; MM – Marmaros massif; RC – Rakhiv cover; PRZ – Pieniny rocks zone; MRZ – Marmaros rocks zone; VGVR – Vygorlat-Gutyn volcanic ridge

Within the Pannonian basin (in PANCAKE profile coordinates: 0–155.000 m) the gravity field is positive, which is due to the relatively shallow location of the MOHO boundary. Its intensity varies in a small interval of values from 0 to +$5 \cdot 10^{-5}$ m/s^2 (after Bouguer gravity anomaly map of the Carpathian-Pannonian Basin System, [Bielik et al., 2004]). In our opinion, the main factor behind the relatively high differentiation of the field (after Bouguer gravity anomaly map of the CELEBRATION 2000 region, [Bielik et al., 2006]) is the influence of the geometry of the basement surface and density boundaries in the sedimentary cover.

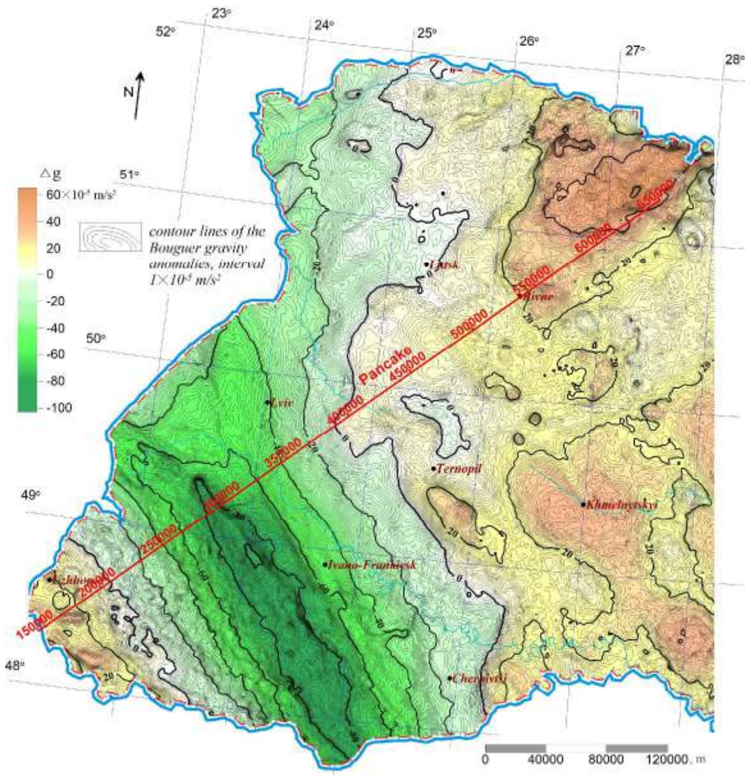

Fig. 4. PANCAKE profile on the gravity field scheme of the Western regions of Ukraine [Scheme of the gravity field of Ukraine, 2002]

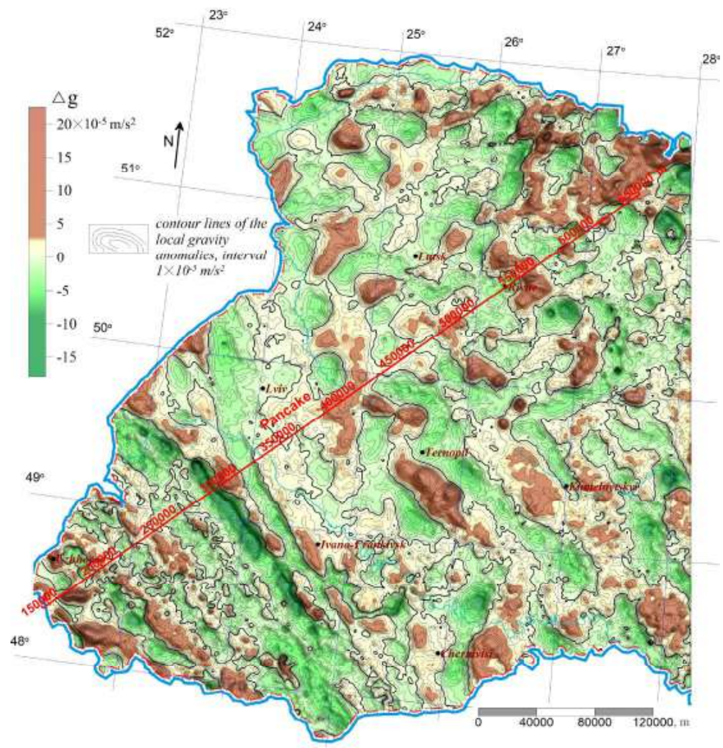

Fig. 5. PANCAKE profile on the scheme of the local gravity anomalies of the Western regions of Ukraine (radius of averaging transformation – 20,000 m)

The gravity field of the Ukrainian Carpathians (in profile coordinates: 155.000–340.000 m, see Fig. 3) has a striped character.

Its intensity decreases in the northeast direction from the Transcarpathian Trough through the Folded Carpathians to the Precarpathian Trough. The tectonics of the Earth's crust and deep inhomogeneities at the border of the OUC and EEC are the reason for the existence of a regional intense Carpathian gravity minimum (up to $-101\cdot10^{-5}$ m/s^2) with large gradient bands (see Fig. 4).

The Transcarpathian Trough (155.000–201.000 m) together with the VGVR is part of the IUC. Molasses deposits of the Neogene (clays, argillites, sandstones), which contain pyroclastic and effusive rocks, most developed in the VGVR body, take part in the Transcarpathian Trough structure. The total thickness of Neogene rocks reaches 2.500–3.000 m. Neogene deposits lie on dislocated Mesozoic rocks. The deepest basement is found in the northeastern part of the Transcarpathian Trough under the VGVR, where the Paleozoic surface lies at a depth of 4,000 m.

The gravity field of the Transcarpathian Trough is positive and of high intensity (up to $+40\cdot10^{-5}$ m/s^2, directly along the profile – $+30\cdot10^{-5}$ m/s^2) and has a boulder-like character. Against the background of regional iso-anomalies, which have a predominantly north-western direction, quite large and intensive anomalies stand out, mostly associated with magmatic activity of fault and volcanic nature. Within the VGVR the intensity of the field decreases to the level of $+10\cdot10^{-5}$ m/s^2.

The VGVR (184.000–201.000 m) is an effusive-pyroclastic series of Neogene volcanic formations that extend in the northern and northeastern parts of the Chop-Mukachiv depression and partially cover the Magury and Porkulec covers. It was established that the VGVR was formed as a result of a series of volcanic eruption stages during the late Sarmatia-Pannonian period.

It is a single complex geological body, represented by layering of lavas and pyroclasts, sometimes with layers of sedimentary (mainly volcanomict) and tuffogenic-sedimentary rocks. Within the gradual decrease of the positive level of the gravitational field, the VGVR begins with a gradient band, where the field intensity decreases from $16\cdot10^{-5}$ m/s^2 to $12\cdot10^{-5}$ m/s^2 (about 184,000 m), and ends in the second gradient band ($7\cdot10^{-5}$–$5\cdot10^{-5}$ m/s^2) (about 201,000 m) (see Fig. 4). On the scheme of gravity anomalies (see Fig. 5), a large negative anomaly (up to $-3\cdot10^{-5}$ m/s^2) is observed over the southwestern part of the VGVR, which (after 194.000 m) turns into a positive anomaly (3.5–$4\cdot10^{-5}$ m/s^2) of complex morphology.

Magmatism is widely developed along the Transcarpathian deep fault: in the northwestern part – Neogene andesitic, and in the southeastern part – Mesozoic of diabase and even ultramafic composition. The foci of most earthquakes are confined to the fault [Maksymchuk, Pyrizhok, Pronyshyn & Tymoschuk, 2014]. Researchers of the Transcarpathian fault [Sollogub et al., 1987; Maksymchuk et al., 2014, etc.] believe that it is the main seismic-tectonic line of the Carpathian region. The Transcarpathian fault is associated with a sharp increase in the thickness of the Earth's crust (by more than 10.000 m) towards the Folded Carpathians, and the MOHO here has a certain slope towards the EEC.

The Pieniny and Marmaros rocks (195.000–200.000 m) are a zone that, together with the Transcarpathian fault, is the border between the Inner and Outer Carpathians. The peculiarity of this cover are the "rocks" of Triassic and Jurassic limestones, which lie in the form of rootless boulders among the red Pukhovo marl. Modern geologists, following V. V. Glushko and S. S. Kruglov, consider the Cretaceous section of the cover as an olisthostrome, and the huge limestone boulders as olistholithes [Gintov et al., 2014; Tectonic map of Ukraine, 2007]. In the area of the PANCAKE profile, boulders of Triassic and Jurassic limestones are overlain by the VGVR rocks [Tectonics of the Ukrainian Carpathians, 1986; Kendzera et al., 2019].

It is very difficult to separate the Transcarpathian deep fault and the Pieniny and Marmaros rocks based on the signs of their manifestation in the Bouguer gravity (see Fig. 4). It is likely that in the north beyond the Chop-Mukachiv depression, the extension of the Transcarpathian fault (201.000–204.000 m) is reflected by an indistinct gradient strip, which ends the zone of positive gravity anomalies; their intensity sometimes reaches $+5\cdot10^{-5}$ m/s^2 (see Fig. 5).

The Folded Carpathians (Outer Ukrainian Carpathians; Ukrainian Flysch Carpathians) (200.000–292.000 m) is a geosynclinal edifice, in which the structures of the first order are large tectonic thrust sedimentary plates-covers with significant horizontal displacements (up to 60.000 m and more) in a cross extension of the Carpathian arc, i.e. in the north-eastern direction. The total thickness of the covers is up to 10.000–15.000 m. According to seismic data of DSS and CMRW, under the Carpathian thrust, the bottom of the Earth's crust reaches maximum depths, more than 50.000 m [Zayats, 2013]. The Carpathian edifice is bounded by deep Transcarpathian and Precarpathian faults.

The Carpathian tectonic covers are formed by complexly dislocated sedimentary rocks of the Cretaceous, Paleogene, and Lower Neogene. From the southwest to the northeast, the PANCAKE profile crosses the Porkulec, Duklyan, Krosno, and Skyba covers (see Fig. 3).

Tectonic covers form bands of gravity gradients of significant size and intensity (see Fig. 4) and large extended zones of positive or negative anomalies (see Fig. 5); these zones are correlated with extension of the covers fronts. The intensity of the Bouguer gravity decreases in the northeast direction from the Transcarpathian fault from zero to significant negative values near the Precarpathian fault. The decrease in the intensity of the Bouguer gravity is associated with a sharp increase in the depth of the basement surface from 5.000 m to a maximum depth of 13.000 m under Skyba napper, as well as a sharp deepening of the MOHO boundary from 25.000–29.000 m (the Pannonian basin) to 35.000–40.000 m (zone of the Transcarpathian fault) and up to 50.000 m and more in the front of the Folded Carpathians, where the known Carpathian gravity minimum (to $-101 \cdot 10^{-5}$ m/s^2; and in the area of the PANCAKE profile it reaches $-90 \cdot 10^{-5}$ m/s^2) has a coordinated extension with the front of the Folded Carpathians and the Precarpathian fault.

The Precarpathian deep fault at the intersection with the PANCAKE profile practically coincides with the northeastern wing of the regional gravity minimum (292.000÷300.000 m), whose axis extends over the Boryslav-Pokuttia napper (see Figs. 3, 4). The Precarpathian fault is a large, relatively wide, linearly broken tectonic structure, along which branches of a lower order and separate complicated areas of tectonic knots are observed. According to seismic and gravity data, within the Ukrainian Carpathians, the fault is composed of a system of main and subordinate 2–3 scarps, which are reflected in the gravity field by localized zones of elevated gradients. In the Boryslav-Vorokhta section, the average amplitude of the group dip fault is 3,000–4.000 m. The hanging wing of the dip fault is turned towards the platform, the lying one – towards the Folded Carpathians. The recumbent wing is complicated by a graben [Anikeyev et al., 2005a]. According to structural and tectonic constructions, the graben is developed within the limits from the city of Dobromyl to the city of Verkhovyna; the average width of the graben is up to 10.000 m; depth – 8,000–10.000 m [Bilichenko, 1999]. Within the dip fault of the Precarpathian Fault, the depth of the basement in the northeast direction sharply decreases from 8.000–10.000 m to 3.000–4.000 m.

The Precarpathian trough (292.000–340.000 m), as it is commonly believed today, includes the Boryslav-Pokuttia and Sambir covers and the Bilche-Volycia autochthonous zone (see Fig. 3). The trough is characterized by an uneven dip of the basement from northeast to southwestern direction, which is reflected by the growth of the striped nature of gravity anomalies and a significant decrease in the field intensity level to the gravitational minimum. The general decrease in the intensity of the Bouguer gravity is complicated by gravity steps, which are caused by dip faults of the northwest extend. The main one is the Precarpathian fault, which was pointed out in the fundamental work by S. I. Subbotin [Subbotin, 1955].

The Carpathian gravity minimum of the regional northwestern extension is caused by a significant increase in thickness of the Earth's crust (the MOHO boundary deepening is estimated to be 50,000–60.000 m [Boyko et al., 2003; Zayats, 2013; etc.]), by a sharp deepening of the basement surface from the southwestern side of the Precarpathian fault (in the strip of the PANCAKE profile, the amplitude of the main dip fault is about 4.000 m) and next the general deepening of the foundation surface to 10.000 m and more. The near-fault thrust of powerful flysch and molasse complexes also contributes to the formation of the gravity minimum. For example, according to the results of geological-gravity modeling along seismic profiles in the East-Dolyna Square, the local part of the minimum could be explained only by the low density of Paleogene rocks of the first tier of folds and by presence near-surface of Neogene salted rocks [Anikeyev et al., 2005b]. In the works [Hontovoy, 1968; Dolenko et al., 1980; Zayats, 2013], it is also noted that the shift of the axis of the regional minimum to the Pre-Carpathian depression is associated with the increase in the thickness of light molasses and salt-bearing rocks they have. The authors of the work share a similar opinion [Starostenko, et al., 2013]: "The gravity low (about -90×10^{-5} m/s^2) over the Carpathian orogen has a pointed shape that indicates a narrow zone of low density (and low-velocity) rocks in the upper layers of the crust, which must be associated with a thick sedimentary sequence". We should also note that the general shift of the Carpathian gravity minimum to the northeast from the Carpathian high system (only in the southeast, in the Verkhovyna region, the axis is close to the highest ridges) is evidence of the Folded Carpathians thrust nature.

The Volyn-Podilsk plate (340.000–552.000 m) is tectonically divided into the Lviv Paleozoic Trough and the Volyn-Podilsk monocline. The crystalline basement of the plate consists of igneous and metamorphic rocks of Archean and Early-Proterozoic age, divided by faults into separate blocks. Its surface gradually rises from a depth of about 8,000 m (at the beginning of the plate) to 1.500–800 m. Along the PANCAKE profile, the thickness of the crust of the platform near the Rava-Rusky fault is 46,000–49,000 m, closer to the Radekhiv-Rohatyn fault it decreases to 41.000–43.000 m, then probably 42,000–46,000 m.

Within the limits of the Lviv Paleozoic Trough, the intensity of the Bouguer gravity gradually increases in the northeast direction from $-45 \cdot 10^{-5}$ m/s^2 to $12–18 \cdot 10^{-5}$ m/s^2 at the border with the Volyn-Podilsk monocline, which is explained by the general elevation of the surface of the crystalline foundation. The field intensity remains at the level of $14–18 \cdot 10^{-5}$ m/s^2 until the Volyn Traps.

The Volyn Traps nappe (552.000–565.000 m) is a series of igneous rocks (tuffs, tufobreccias). The trap layer includes basalts, diabases, etc. [Geological map of Ukraine, 2007]. Above the Traps nappe, the Bouguer gravity increases sharply to $35·10^{-5}$ m/s^2, and beyond it, in the north-eastern direction, it decreases to $25·10^{-5}$ m/s^2 (see Figs. 3, 4). The Volyn Traps are developed in the near-surface part of the section and have a thickness of 200 m, possibly more, if that intense positive anomaly (it coincides with nappe contour in this zone of the profile, see Figs. 3, 5), caused by these Traps.

The Volyn-Podilsk Trough (565.000–600.000 m) is the beginning of the western slope of the USh. Layered intrusions, dykes, and basalt covers are common here, and that is associated with the existence of deep faults [Kendzera et al., 2019]. Sandstones, marl, limestone, and chalk are present in the low-thickness sedimentary cover section (about 500–1000 m).

The deepening of the basement surface at the beginning of the Volyn-Podilsk Trough (565.000–580.000 m) is reflected by negative gravity anomalies (up to $-3·10^{-5}$ m/s^2, see Figs. 3, 5). In the profile interval (580.000–592.000 m), an intense positive gravity anomaly (up to $+7·10^{-5}$ m/s^2) is caused by a sharp uplift of the basement. The next in profile (592.000–610.000 m) is a zone of negative local gravity anomalies (up to $-5·10^{-5}$ m/s^2, see Fig. 5) – due to the depression in the surface of basement and due to change of composition and, accordingly, in rocks physical properties at the boundary between the Volyn-Podilsk Trough and the Volyn-Polisie volcano-plutonic belt; the zone reflects a smooth transition between these two tectonic units.

The Volyn-Polisie volcano-plutonic belt (600.000–650.000 m) is included in the northwestern part of the USh. Precambrian rocks of the crystalline basement practically reach the Earth’s surface. The basement is mainly represented by leptite, diorite-granodiorite and granite formations and granitoids of the Lower Proterozoic, among which metamorphosed sedimentary and sedimentary-volcanogenic formations are present in the form of xenoliths [Geological map of Ukraine, 2007].

From the Volyn-Podilsk Trough to the end of the PANCAKE profile, the intensity of the significantly differentiated gravity field increases from $+28·10^{-5}$ m/s^2 to $+44·10^{-5}$ m/s^2. The complex morphology, truncation, and high intensity of local gravity anomalies within the Volyn-Podilsk Trough and the Volyn-Polisie belt are caused by the proximity of the basement to the earth's surface and the high differentiation of the crystalline rocks physical properties.

On the platform part of the PANCAKE profile, gravity local anomalies and high-gradient zones (see Fig. 5) are caused by basement blocks and faults, mainly in the northwest direction, as well as inherited structures of the sedimentary cover. “Multidirectional movements of the basement blocks caused the formation in the sedimentary cover of interblock fault zones and a series of stamp uplift and depression” [Polishchuk, 2011].

It should be noted that the uplift of the basement surface within the EEC towards the USh has a regional character, therefore it is not reflected in the local gravity anomalies (see Fig. 5), but is a regional part of the Bouguer gravity (see Fig. 4).

Initial data and modeling technique

The initial data used in the process of gravity modeling of the structure of the Earth’s crust can be divided into three groups: the first – geophysical observations data and the tectonic interpretation of seismic models; the second – geological and tectonic maps, seismogeological and geodensity cross-sections on closely located profiles, and the third – limiting data regarding the geometry and densities of the sedimentary cover, basement and upper mantle from previous studies by various authors.

Tectonic interpretations of the seismic model of the structure of the earth's crust and upper mantle according to the PANCAKE profile [Starostenko et al., 2013; Verpakhovska et al., 2018] is the structural-tectonic basis for continued geophysical research. Additional geophysical fields, primarily gravity field anomalies, transfer the process of processing and interpreting geophysical data into the plane of complex interpretation. The purpose of complex interpretation is to build a more reasonable model, consistent with geophysical fields and, obviously, more adequate to the real structure of this tectonically complex region.

In the process of building a density model based along the PANCAKE profile, the following materials were taken into analysis:

– tectonic maps of Ukraine Western regions [Tectonic map of Ukraine, 2007, Zayats, 2013];

– Bouguer gravity of Ukraine Western regions [Scheme of the gravity field of Ukraine, 2002];

– seismic model of the structure of the Earth’s crust and upper mantle and its tectonic interpretation along the PANCAKE profile [Starostenko et al., 2013; Verpakhovska et al., 2018];

– geological model along the Slavske-Stryi-Peremyshlyany seismotraverse (R2) [Zayats, 2013];

– seismic model of the lithosphere along geotraverse II [Sollogub et al., 1987; Zayats et al., 1987];

– density model of the lithosphere along geotraverse II [Starostenko et al., 1987];

– schematic geological cross-section on the line A1–A2 [Geological map of Ukraine, 2007];

– MOHO geometry model under the Carpathians according to the Airy – Heiskanen isostasy hypothesis [Marchenko & Maksymchuk, 2013];

The tectonic interpretation of the migrated seismic image along the PANCAKE profile (Fig. 6) demonstrates good consistency with geological data, as well as with seismic surveying in Ukraine along profiles R1 and R2, located north and south at a distance of 20–30 km parallel to the PANCAKE profile (see Fig. 3).

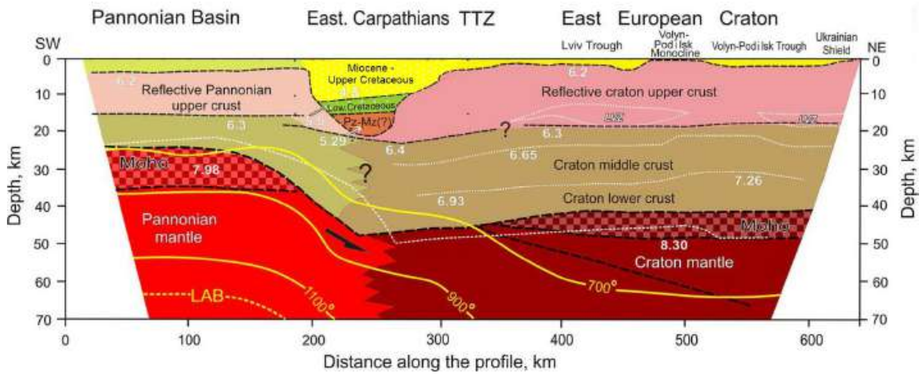

Fig. 6. Tectonic interpretation of the transition between the EEC and Eastern Carpathians in the area of the Teisseyre-Tornquist Zone (TTZ or TESZ – see fig. 2) to ALCAPA microplate (Pannonian Basin) along the PANCAKE profile (modified after Verpakhovska et al., 2018)

Black dashed lines correspond to migrated seismic boundaries of the basement, in the Carpathian trough and in the upper crust (thin dashed lines) and at the Moho – upper mantle depths (thick dashed lines); chess shading outlines thick transition zone at the Moho from lower crust to the upper mantle. Crustal layers (white dotted lines) and velocities in km/s (white color numbers) are taken from the velocity model of [Starostenko et al., 2013]. Upper mantle isotherms (yellow contour lines) are taken from [Kutas, 2014]. Lithosphere-asthenosphere boundary (LAB) below the Pannonian Basin [Horváth, 1993]

Seismic profile R2 from southwest to northeast crosses the central part of the OUC (Krosno and Skyba nappes), Precarpathians Trough (Boryslav-Pokuttia flysch nappe, Sambirsky molasse thrust, Bylche-Volycia autochthonous zone) and Lviv Paleozoic Trough on the southwestern edge of the EEC. According to the geological model of the R2 seismic profile (after Kh. B. Zayats, Fig. 7) flysch complex reaches its maximum thickness (13 km) within Skyba. The lower part of the flysch (7–13 km deep) is represented by a para-autochthonous layer of Cretaceous and, probably, Paleogene.

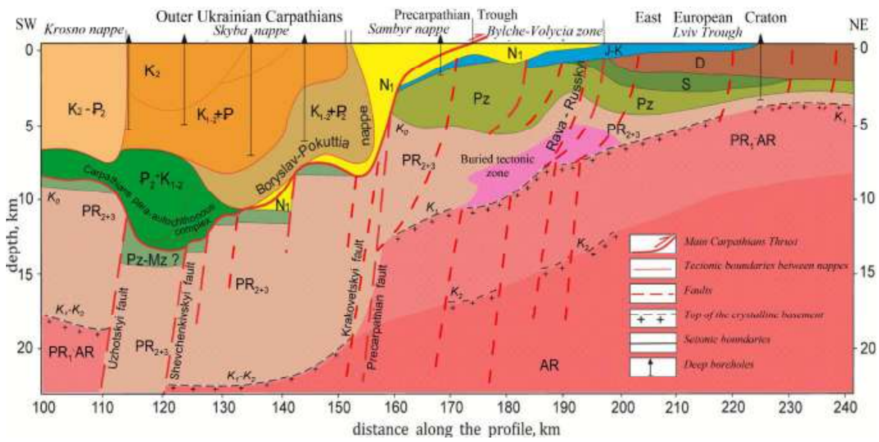

Fig. 7. Geological model along the Slavske-Stryi-Peremyshlyany seismic profile (R2) [Zayats, 2013]

K_0 – the surface of the folded Riphean basement – the pre-Alpine base of the Carpathians (above PR_{2+3}); K_1 is the surface of the pre-Ryphean crystalline basement (above PR_1+AR); K_2 is the surface of the proto-basement (the reflective horizon within the granite layer). Buried tectonic zone – endogenous intrusive processes zone, probably related to the development of the proto-basement and TESZ (TTZ)

The Mesozoic-Paleozoic autochthonous base of the Ukrainian Carpathians lies on the Riphean basement (surface K_0) at depths from 8 km to 15 km under the Skyba. The surfaces of the Doryphean crystalline basement (K_1) and protobasement (K_2) along the profile dip from the northeast to the southwest and reach a depth of about 23 km under the Skyba nappe. The plunge of the crystalline basement to the southwest is associated with the Carpathian orogen formation and is complicated by a number of faults (Rava-Russkyi, Precarpathian, Krakovetskyi, Shevchenkivskyi, Uzhotskyi, and others). Under the Precarpathian Trough within the Buried tectonic zones (see Fig. 7) deep intrusions are predicted that can reach the bottom of the sedimentary cover. These zones were identified on the basis of changes in the dynamic characteristics of the wave pattern [Zayats, 2013]. In terms of location and size, the geological model of the Carpathian structure along profile R2 fits very well into the tectonic interpretation along the PANCAKE profile (see Fig. 6) and into the seismic model along the Geotraverse II (Fig. 8).

The geological model of the Carpathian edifice (see Fig. 7) is the basis for the geometry of the density model in this part of the PANCAKE profile.

To form the geometry of the initial density model of the Earth's crust on the PANCAKE profile outside the OUC (in the southwest within the Pannonian basin and Transcarpathian Trough and in the northeast within the EEC) tectonic interpretation (see Fig. 6) and seismic cross-section in the Berehove-Korets part (see Fig. 8) were used. Also, the geological profile along the A1-A2 line is taken into account in the defined geometry of the sedimentary cover on the southwestern slope of the EEC [Geological map of Ukraine, 2007]. The location of the specified profiles is shown in Fig. 3.

Within the OUC zone, geometry of the K_0 and $K_{1–2}$ surfaces is reproduced according to the seismogeological section along the R2 profile; outside the OUC of surfaces K_0, K_1 and K_3 – according to the seismic model along geotraverse II, taking into account the tectonic interpretation of the PANCAKE seismic profile.

In the Folded Carpathians region according to the DSS along geotraverse II, the K_0 horizon is traced at depths of 4–12 km (limit velocities vary from 5.4 km/s to 5.6 km/s). It is the surface of the upper Proterozoic (Ripheus). Perhaps it has a continuation to the southwest into the Transcarpathian Trough. The most extensive, almost along the entire geotraverse II, is the surface of the Doryphean crystalline basement (the surface of the granite layer – the K_1 horizon). Its depth varies from 0 to 23 km (5.6–6.5 km/s): from 3.6 km the USh, the K_1 horizon deepens from 0.6 km to (near the Radekhiv-Rohatyn fault, 6.0–6.2 km/s), where it begins to deepen sharply to 10–12 km, and under the Folded Carpathians – to 23 km.

The K_2 horizon is identified with the ancient surface of the consolidated crust in the early stages of its development. It lies at depths of 6–12 km on the USh slope and within the Volyn-Podilsk monocline. Under the OUC, the horizon is traced uncertainly, its depths are approximately the same as K_1, so it is generally assumed that the complex boundary K_{1+2} is recorded here. At depths from 14 km to 23–25 km, according to the DSS, the K_3 horizon (6.8–7.0 km/s) is traced. Perhaps this is the surface of the basalt layer, but it cannot be the Conrad surface due to the high (9–20 km) level of occurrence in the Earth's crust [Zayats, 2013]. Under the Pannonian Basin, it lies at depths of 14–16 km; under the Precarpathian Trough, it deepens to 28–30 km (Boryslav-Pokuttia and Sambyr nappes) and up to 23 km (Bylche-Volycia zone). On the slope of the EEC, the K_3 horizon can be reliably traced: at depths of 20–21 km in the Lviv Trough, further to the northeast within the EEC it may deepen a little, and closer to the USh it rises somewhat [Sollogub et al., 1987; Zayats et al., 1987; Sollogub et al., 1993]. The K_3 horizon is absent under the Carpathians.

For the formation of the geometry of the density model, it is important to determine the faults in the Earth’s crust, primarily deep ones, which separate large structural blocks of the lithosphere. According to the results of the interpretation of seismic data (characteristic changes in the wave pattern of a number of CMRW profiles and an exceptionally large amplitude of up to 5 km), most confidently along the Boryslav-Pokuttia nappe front is traced the Precarpathian fault (see Fig. 7). The Uzhotskyi fault, which is distinguished by sign of the crystalline basement surface rise, is also pronounced. Four deep faults of significant amplitude (Precarpathian, Uzhotskyi, Chornoholovskyi, and Transcarpathian) form a block-deep structure of the Earth’s crust under the Carpathian edifice [Zayats, 2013]. The first two faults form a negative structure called the Subcarpathian graben by G. Yu. Boyko [Boyko & Anikeyev, 1990; Boyko et al., 2003].

Under the Carpathians, K-M (7.5–7.6 km/s) and M (up to 8.2 km/s) horizons were registered deeper than the K1+2 horizon along geotraverse II. Within the Carpathians, they tend to deepen in the northeast direction by more than 10 km (see Fig. 8). The crust-mantle horizon is characteristic of active rift geostructures. The minimum thickness of the Earth's crust was registered under the Transcarpathian Trough and the Pannonian depression – 25–30 km. This zone is separated from the OUC by the Transcarpathian fault. The fault is the main seismotectonic zone of the Carpathians [Maksymchuk, et al., 2014], and it is also associated with a sharp increase in the thickness of the crust in the northeastern direction under the Folded Carpathians up to 50 km or more [Sollogub et al., 1987; Marchenko & Maksymchuk, 2013, etc.]. According to the longitudinal seismic profile RP-VI (see Fig. 3), the MOHO boundary lies at depths of 52–56 km [Zayats, 2013]. Further to the northeast from the Lviv Trough to the Volyn-Podilsk monocline according to geotraverse II MOHO lies at depths of 38–40 km. For the initial density model within the EEC, we chose the MOHO depth interval from 40 km to 45 km, where the maximum depth is 45 km under the outer part of the Volyn-Podilsk monocline. In general, these depth variations fit within the boundaries of the MOHO zone, which is significant in thickness according to the tectonic interpretation [Verpakhovska et al., 2018].

For the density model along the PANCAKE profile, the initial values of the density of the sedimentary cover, crust, and upper mantle were estimated based on the data of the geotraverse II density model (Fig. 9) using the calculated density values in the work [Tašárová et al., 2016] for the main tectonic units: ALCAPA, EEC and Eastern Alps according to the seismic profiles of the CELEBRATION 2000 experiment (see Fig. 1). Data from [Antipov, Melnichuk & Lizanets, 1969; Mayevsky et al, 2012; Anikeyev, Maksymchuk & Pyrizhok, 2021; Makarenko, 2021] were also taken into account.

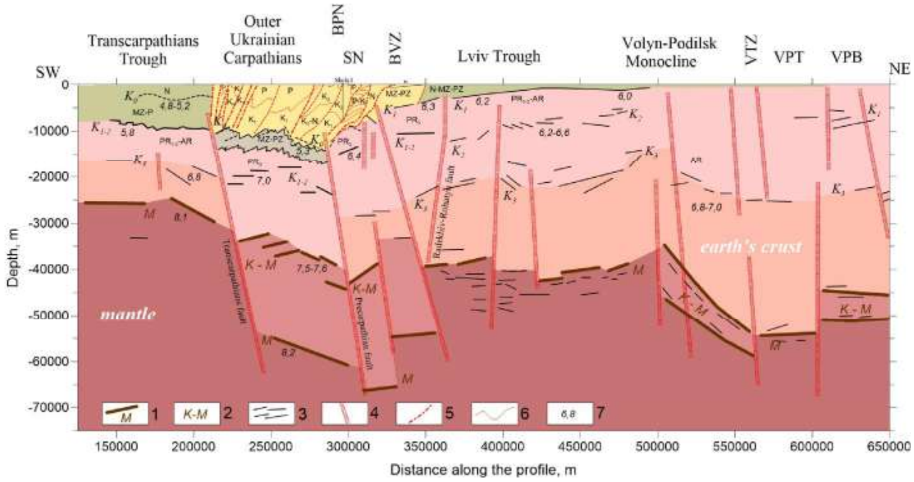

Fig. 8. Seismic cross-section of the lithosphere in the Berehove-Korets part of the Geotraverse II (modified after Sollogub et al., 1987; Zayats et al., 1987)

Tectonic zones: BPN – Boryslav-Pokutttia Nappe; SN – Sambir Nappe; BVZ – Bilche-Volycia Zone; VTZ – Volyn Traps Zone; VPT – Volyn-Podilsk Trough; VPB – Volyn-Polisie Belt. Legend: 1 – MOHO interface; 2 – crust-mantle substrate; 3 – reflecting areas (horizons K_0, K_1, K_2, K_3 and waveguide – deep seismic waveguide); 4 – deep faults; 5 – main faults in the sedimentary cover; 6 – lines of uncoordinated deposition of sedimentary rocks; 7 – velocity of refracted waves, km/s. The Geotraverse II is parallel to the PANCAKE profile, therefore, for the convenience of its analysis, it is provided in the projection of PANCAKE coordinates

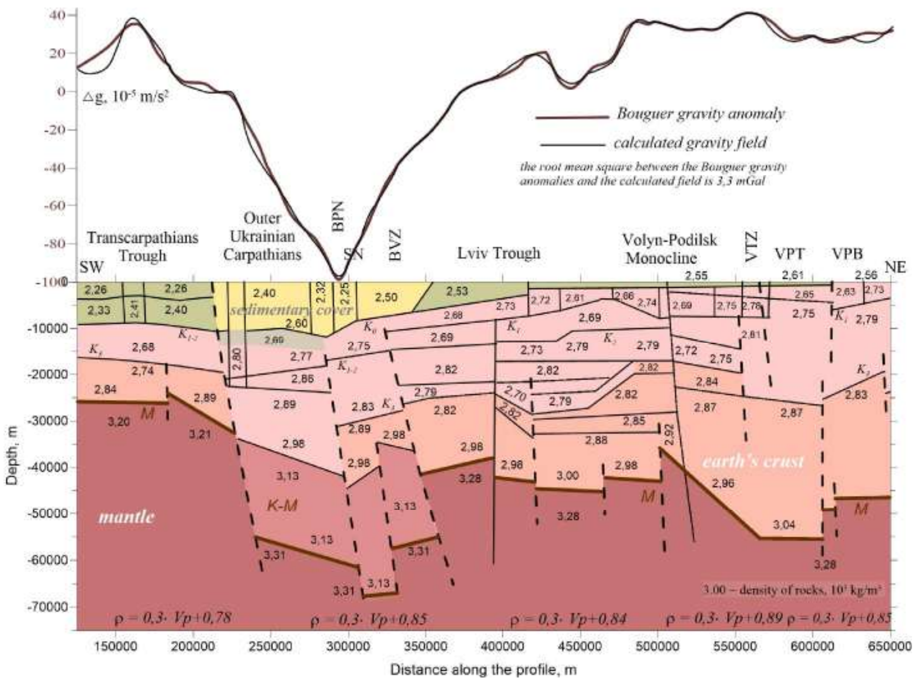

Fig. 9. Density model of the lithosphere in the Berehove-Korets part of Geotraverse II (after Starostenko et al., 1987)

Black thin lines indicate density boundaries; black dashed lines – faults; MOHO boundary is a thick brown line. Below the section on individual sections of the profile, the equation of the correlation relationship between the speed of longitudinal waves and the densities, for which the coefficients were refined in the process of the gravity inversion solving, is given. Other explanation as in Fig. 8

Thus, 2.99×10^3 kg/m^3 was chosen for the lower part of the crust within the Pannonian Basin (in the work [Tašárová et al., 2016], the interval from 2.78×10^3 kg/m^3 to 3.00×10^3 kg/m^3 was given). The density model along the CEL09 profile [Godová, 2021] in part of the Pannonian Basin was also analyzed.

In determining the trends in the density change of the Earth's lower crust and upper mantle along the PANCAKE profile behavior of the P-wave velocity in seismic models [Starostenko et al., 2013; Verpakhovska et al., 2018] was taken into account.

Further refinement (selection) of the parameters of the initial density model was carried out by the method of gravitational modeling, which was aimed at minimizing the discrepancies between model field (the gravitational anomalies calculated for the model) and the Bouguer gravity. The parameters of the density model (geometry and density of sedimentary strata, blocks of the basement and upper mantle) have been refined within the limits determined by the above source materials. Refinement (modeling) methods follow two directions: the method of simple selection, which is based on the solution of direct problems, and the automated solution of the inverse problem of gravimetry. We consistently use both directions.

The methodological principle of quantitative interpretation of gravimetric materials, given the wide equivalence of solutions of the gravity inversion, is the mandatory preliminary formation and achievement in the modeling process of “optimal” geological-tectonic and physical properties of a single solution. The resulting density model should correspond to the Bouguer gravity (with a predicted error) and deviate minimally (be “optimal”) from the a priori known complex of geological and geophysical materials. Both criteria are equally important.

Thus, in the work [Starostenko et al., 1987], when constructing density models along geotraverse II, they proceeded from the postulates about experimentally established statistical dependencies between the density and velocity of longitudinal waves, as well as about the identity of the position of the velocity boundaries and density boundaries. The initial density model was determined by the general statistical relationship between density and velocity. According to the results of the regression analysis of the residual field (the difference between the Bouguer gravity and model field) for each tectonic zone in the cross-section, blocks with connections different from the general one are distinguished. For these blocks, the gravity inversion was solved to refine the coefficients of the regression equations between density and velocity. According to the described method of quantitative interpretation of the gravity field, the purpose of solving the gravity inversion is the following: on the basis of the initial information, namely, the seismic-velocity model and a priori information about the correlations dependences between of velocity of longitudinal waves and density of rocks along cross-section and the Bouguer gravity anomalies, to construct density model, the calculated gravity field of which will coincide with the Bouguer gravity in a certain approximation. The resulting density model with refined correlations for different blocks generally corresponds to the geotraverse II seismic model (see Figs. 8, 9).

The process of 2D gravity modeling takes place in accordance with the methodological principles of quantitative interpretation of gravimetric materials, so it, like other modeling methods, such as those described in [Grabowska et al., 2011], consists of several stages:

The first stage involves the analysis of geological and geophysical data and the construction of the initial model of the geometry of layers and blocks of the Earth's crust.

The second stage involves determining the initial density model of the mantle, the crystalline part of the crust, and the sedimentary cover.

At the third stage, interactive gravimetric modeling, which is based on simple matching methods (selection from results of gravity direct problem solution), specifies the values of the mantle density or MOHO geometry.

At the fourth stage, in order to bring the model field closer to the Bouguer gravity, corrections are made to the initial values of the densities of the crust and sedimentary cover or geometry of their layers and blocks.

At the fifth stage, the densities in the upper part of the crust model and in the sediment cover are detailed using the methods of the automated solution of the gravity inversion.

The automated solution of the gravity inversion is based on the theory of the criterion approach [Kobrunov, 1985, 1995; Anikeyev, 1999], where mathematical tools are aimed at ensuring solutions with “optimal” properties: the resulting density model should correlate as much as possible with the a priori constructed initial density model within substantiated (reasonable) limits, and model field should deviate from the Bouguer gravity with a given error.

The modeling method is subordinated to the purpose of decision of the gravity inversion [Anikeyev, 1999; Anikeyev et al., 2017, 2019]. There are no restrictions on the complexity of the density model geometry in the methods of solving direct and inverse problems used in this work, except for the usual step with which the Bouguer gravity is given and the chosen discretization of the model by depth. The parameters of the discretization (approximation grid) of the model along PANCAKE profile are as follows. The step by which the Bouguer gravity and discretization of the model along the profile is set – 250 m; profile length – 650 km; discretization of the model by depth –

100 m in the first 0–4000 m; to a depth of 10.000 m – 200 m; then the discretization steps increase in intervals: 10.000–20.000 m – 250 m, 20.000–40.000 m – 500 m, 40.000–80.000 m – 1.000 m.

In terms of depth, the model is limited to a plane at the level of 80 km, below which, in the first approximation, the density distribution is considered spherically symmetric and this distribution coincides with the standard density model of the Earth (under the model an inhomogeneity of lithosphere and asthenosphere are neglected). The selection of a constant for the level of the model field is also programmed, such that the model field is as close as possible to the Bouguer gravity. The concepts of the standard model of the Earth and constants are nominal [Starostenko et al., 1987]. Calculations are performed for a model of excess masses defined relative to the standard model of the Earth. Unlike the simulation [Starostenko et al., 1987], where "sufficiently" thin layers are used to determine excess masses, for this simulation there is a single layer in which the density model is "located". The thickness of this layer is equal to the selected maximum modeling depth – 80 km. The layer density is selected according to the principle of minimum deviation of the model field from the Bouguer gravity (that is, the selection of the level constant of the model field is optional). For modelling along PANCAKE profile density this layer (medium which contains the model) is equal to $3.05{\times}10^3$ kg/m^3.

Results of modeling

The resulting density model of the deep section of the Earth's crust and upper mantle along the PANCAKE profile is presented in Fig. 10. The model corresponds to the Bouguer gravity anomalous and is based on the above geological and geophysical materials. The root-mean-square discrepancy between the Bouguer gravity and gravitational anomalies calculated for the model (model field) is $1.2{\times}10^{-5}$ m/s^2.

The intensity and morphology of local gravity anomalies mainly depend on the sedimentary cover parameters and the basement surface geometry, if it is at shallow depths (3÷5 km and less).

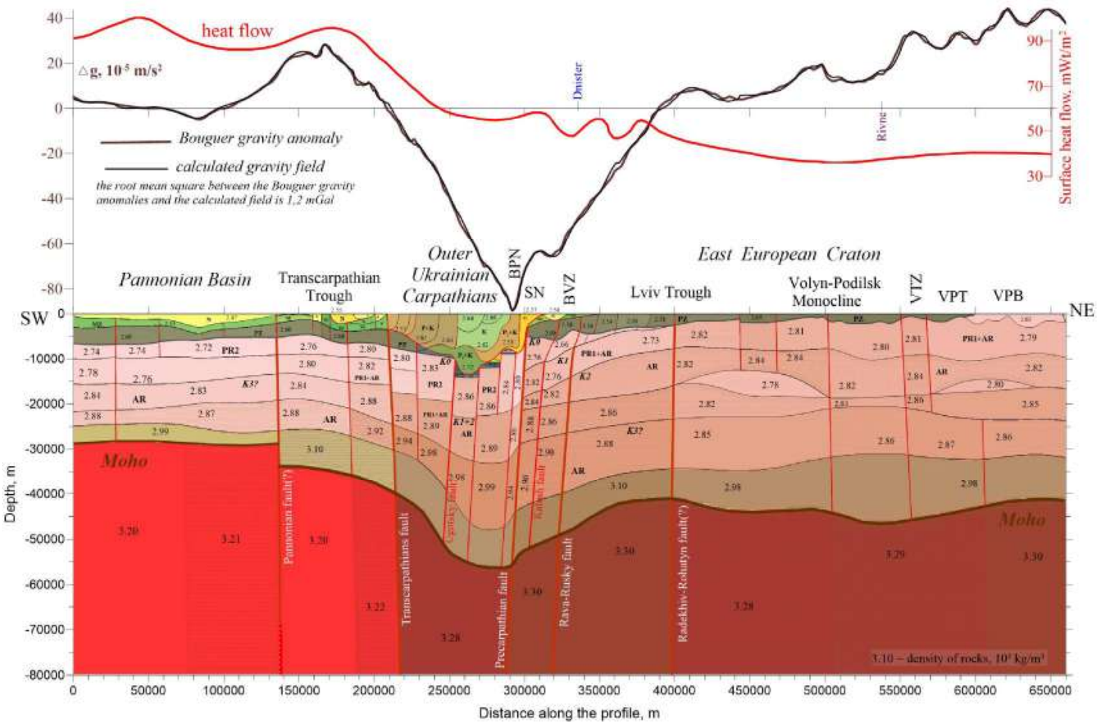

Fig. 10. Density model of the earth's crust and upper mantle along the PANCAKE profile

Black thin lines correspond to density boundaries into sedimentary cover and basement, in the Carpathian trough and in the crust; at the MOHO – upper mantle depths (thick brown line). A red line above the border K_0 between the Transcarpathian and Precarpathian faults is a heterogeneous Mesozoic-Paleozoic autochthonous base of the Carpathian thrust. Red thin lines outline the configuration of the fold-and-thrust belt of the OUC according to geological cross-section along R2 profile [Zayats, 2013]. The red subvertical lines outside the OUC are faults. Surfaces into basement: K_0 – the surface of the folded Riphean basement is the pre-Alpine base of the Carpathians (over PR_2); K_1 – the surface of the pre-Riphean crystalline basement (over PR_1+AR); K_2 – the surface of the protobasement (reflective horizon in the granite layer); K_3 – probable boundary defined as the surface of the "basalt" layer [Sollogub et al., 1987; Zayats et al., 1987]. Terrestrial heat flow data are taken from [Kutas, 2014]. Other explanation as in Fig. 8

Thus, in the northeast of the PANCAKE profile within the EEC, the gravity-active basement surface was matched to parameters of the local Bouguer anomalies. Its geometry fully corresponds to the geological structures within the R2 profile (see Fig. 7), and its depth in the northeast outside the R2 are generally consistent with the geological section [Geological map of Ukraine, 2007].

Depth of the basement surface within the Volyn-Podilsk monocline gradually decreases to 800 m; further, closer to the USh, it increases to 2.000 m, and at the USH the basement comes to the Earth’s surface.

The regional increase in the Bouguer gravity intensity within the EEC is explained by the approach to the Earth’[s surface of more compacted Archaean-Proterozoic rocks. And the Bouguer gravity anomalies is complicated by the influence of Paleozoic layers, the geometry of the basement surface, and low velocity zones (LVZ – see Fig. 6; in [Starostenko et al., 2013] the zones are designated as low velocity layers – LVL).

In the southwest, within the Transcarpathian Trough, a large positive gravity anomaly is due to the general uplift of deep compacted blocks of Paleozoic ($2.60–2.68\times10^3$ kg/m^3), Proterozoic and Archaean ($2.76–3.10\times10^3$ kg/m^3), as well as due to sharp rise MOHO boundary to a depth of 33 km. Extension of anomaly towards the Pannonian basin is limited by the influence of the layers and blocks with low density: Neogene (2.47×10^3 kg/m^3) and Mesozoic (2.53×10^3 kg/m^3), consolidated crust ($2.72–2.99\times10^3$ kg/m^3) and upper mantle (3.20×10^3 kg/m^3).

Within the Pannonian basin, the depths of Paleozoic deposits vary from 2 km (near the Transcarpathian Trough) to 4.5 km (in the depression, near 80,000 m along the profile); of basement – in the interval from 5 km to 6.5 km. According to the results of gravity modeling, the depth of the MOHO boundary under the Pannonian Basin reaches 28–29 km. In the profile interval of 50.000 m–100.000 m, a negative local anomaly (up to $–4.5\times10^{-5}$ m/s^2) is explained by the deepening of the Mesozoic surface and the influence of Neogene strata low density.

Beyond the OUC, the boundaries from the surface of the Riphean basement (K_0) to the lower part of the Earth's crust generally correspond to the tectonic interpretations [Starostenko et al., 2013; Verpakhovska et al., 2018], seismic [Sollogub et al., 1987; Zayats et al., 1987] and density [Starostenko et al., 1987] models along Geotraverse II.

The gravity modeling results do not contradict the existence of LVL zones (correspondingly, low values of densities) present in the seismic model along the PANCAKE profile [Starostenko et al., 2013].

Carpathian gravity minimum and OUC. The structure of the OUC thrust flysch complex and the block structure of the Riphean basement and protobasement shown in Fig. 7 fit very well into the Carpathian gravity minimum. In our model, small changes occurred only in the geometry of the Boryslav-Pokuttia nappe (its extension near to the day surface in the southwest direction was extended).

The morphology and intensity of the local part of the gravity minimum is primarily influenced by the powerful thrust flysch complex and the para-autochthonous complex, which is above the autochthonous Mesozoic-Paleozoic base. The displacement of the gravity minimum closer to the frontal part of the Precarpathian Trough (Borislav-Pokuttia nappe), i.e. in the northeast direction from the projection of the central axis of the zone of deep occurrence of the MOHO, is associated with the increase of thickness molasses and salt-bearing rocks in nappe (they are characterized by low density). The narrowing (sharpening) of the gravity minimum is caused by the lateral influence of rocks with a greater density compared to the Boryslav-Pokuttia rock layers [Anikeyev et al, 2005a; Anikeyev et al, 2005b; Zayats, 2013].

The geometry of the crust and the depths of the MOHO under the OUC cause the regional component of the Carpathian gravity minimum. Here, the maximum depths of the Doryphean crystalline basement (protobasement?) surface up to 23 km also correspond to the deepest submergence of the MOHO surface (up to 54–56 km).

The thickness of the Earth’s crust (depths of the MOHO boundary). For the initial density model, under the OUC we chose the maximum depth of the MOHO to 62 km. However, with different probable values of the density for the crust (some increase in velocities in the seismic model [Starostenko et al., 2013] under OUC also should be taken into account), the calculated minimum of Bouguer anomalies did not rise above $–100\times10^{-5}$ m/s^2. The most likely, in our opinion, the maximum depth of MOHO, which is consistent with the Carpathian gravity regional minimum (up to $–90\times10^{-5}$ m/s^2) and with the probable density for the lower part of the crust of 3.10×10^3 kg/m^3 (selected according to [Tašárová et al., 2016]) is a depth of 54–56 km.

In the density model under the Transcarpathian Trough and the EEC, depth boundaries and MOHO generally correlate with tectonic interpretation [Verpakhovska et al., 2018] and with seismic models [Sollogub et al., 1987; Starostenko et al., 2013]. Under the Pannonian Basin, the MOHO boundary lies at greater depths – 27–30 km; the values of the densities of the main layers of the crust and the sedimentary cover are close to the data [Tašárová et al., 2016; Hrubcová et al., 2010].

The table shows the generalized results of gravity modeling of the Earth's crust cross-section for the main tectonic units along PANCAKE profile. The generalized results agree well with the tabular materials of the article [Tašárová et al., 2016]. Separately for rocks of the sedimentary cover in Fig. 11 presents their stratigraphy and limits of change in density.

Summary of the results from gravity modeling earth crust cross-section along the seismic profile PANCAKE: depths (m) and densities (10^3 kg/m^3) of the main tectonic units

Unit	Sediment infill (over K_0)/ depths and densities	Upper Crust (K_0–K_3?)/ depths and densities	Middle Crust (K_3? – ?)/ depths and densities	Lower Crust (?–MOHO)/ depths and densities	Upper mantle/ densities
PB (ALCAPA)	5000–7000 2.47–2.61	13000–16000 2.72–2.78	24000–27000 2.83–2.88	28000–29000 2.99	3.20–3.21
IUC	4000–6000 2.47–2.68	13000–16000 2.76–2.82	26000–30000 2.84–2.92	34000–40000 3.10	3.20–3.22
OUC	5000–15000 2.50–2.72	17000–23000 2.80–2.86	30000–48000 2.86–2.99	40000–56000 3.10	3.28
PT+TESZ	3000–4000 2.50–2.60	17000–21000 2.64–2.84	35000–43000 2.86–2.90	41000–54000 3.10	3.30
EEC	500–3000 2.50–2.66	16000–19000 2.78–2.84	31000–35000 2.82–2.88	41000–46000 2.98–3.10	3.28–3.30

PB – Pannonian Basin; ALCAPA – Alps-Carpathian-Pannonian; IUC – Inner Ukrainian Carpathians (Transcarpathian Trough); OUC – Outer Ukrainian Carpathians; PT – Precarpathian Trough; TESZ – Trans-European Suture Zone; EEC – East European Craton.

Tectonic interpretation of the density model. In the density model under the OUC in the lower part of the Earth's crust, the density is equal to 3.10×10^3 kg/m^3, which may mean the presence of significant masses of eclogite [Mjelde et al, 2013], which some researchers attribute to the roots of the Earth's crust or to the intermediate crust-mantle layer. Also, this work states that eclogite facies are developed, as a rule, in subduction zones. Their density can reach up to 3.30×10^3 kg/m^3.

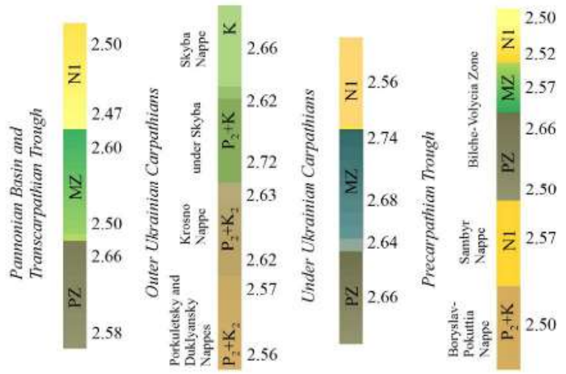

Fig. 11. Stratigraphy of sedimentary cover rocks (over boundary K_0) and Densities, 10^3 kg/m^3, along the PANCAKE profile

Within the OUC, the boundary between the granite and basalt layers (Conrad boundary) is not identified: either the granite layer gradually transitions into the basaltic layer or it is very thin. Outside the OUC, the probable surface of the basaltic layer is designated as the K_3 boundary (according to [Sollogub et al., 1987; Zayats et al., 1987]). We chose this boundary as the conventional boundary between the middle and upper crust. The transition from the middle to the lower crust is identified by a sharp increase in rock density by more than 0.1×10^3 kg/m^3, in particular to 2.98–2.99×10^3 kg/m^3 outside the OUC, and under the OUC – up to 3.10×10^3 kg/m^3.

Deep faults, some of which probably penetrate the upper mantle, play an important role in shaping the tectonics of the region [Zayats, 2013], so they are reflected in the tectonic interpretation of the density model (Fig. 12).

Discussion

The resultant density model along the PANCAKE profile provides new information about the structure of Earth's crust upper part, about basement topography and MOHO, especially this applies to the Ukrainian Carpathians, where there are the greatest discrepancies in the estimation of the MOHO depth.

Depths of MOHO and densities within ALCAPA. According to the seismic model [Starostenko et al., 2013], the Earth's crust thickness here is 22–25 km. In the tectonic interpretation [Verpakhovska et al., 2018], the MOHO depths transition zone are given in the range of 24–35 km. In the density model along the S04 profile (southeast trending profile; see Fig. 1), the MOHO depth is determined in the interval of 25–30 km; the densities: the upper mantle – 3.20×10^3 kg/m^3, lower crust – 2.9–3.05×10^3 kg/m^3, middle crust – >2.80×10^3 kg/m^3, upper crust – >2.60×10^3 kg/m^3 [Hrubcová et al., 2010]. Along the CEL01 profile the

MOHO lies in the interval of 28–30 km [Janik et al., 2011]. According to the results of research [Tašárová et al., 2016] the MOHO depth is from 25 km and mantle density is $3.25{\times}10^3$ kg/m^3 and more.

In our density model along the PANCAKE profile, the thickness of the ALCAPA crust is 28–29 km; the density of the lower crust is $2.99{\times}10^3$ kg/m^3; the density of the upper mantle is 3.20–$3.21{\times}10^3$ kg/m^3. Certain differences in the thickness of the Earth's crust and the densities of the upper mantle under the Pannonian Basin may be due to the fact that the CELEBRATION 2000 (CEL01 and other profiles) research area is located west of the Ukrainian border.

Depths of MOHO and densities within the Carpathian Orogen. Densities in a section with depth from the sedimentary cover to the upper mantle, as well as velocities, change (increase) to a more intense than along the profile from one tectonic unit to the next. This is the main reason for the significant regional dependence of the gravity field intensity on the basement deepening and MOHO. This dependence clearly outweighs the influence of the increase in the density of crustal blocks under and on both sides of the OUC, i.e. under the Carpathian accretionary prism. The increase in density, which is the largest on the side of the Transcarpathian Trough – up to $0.1{\times}10^3$ kg/m^3 (as well as velocities, see Figs. 6, 8), is possibly related to subduction processes, and its certain symmetry is relative to the greatest deepening of the MOHO, which is also reflected in the Bouguer gravity, needs an explanation.

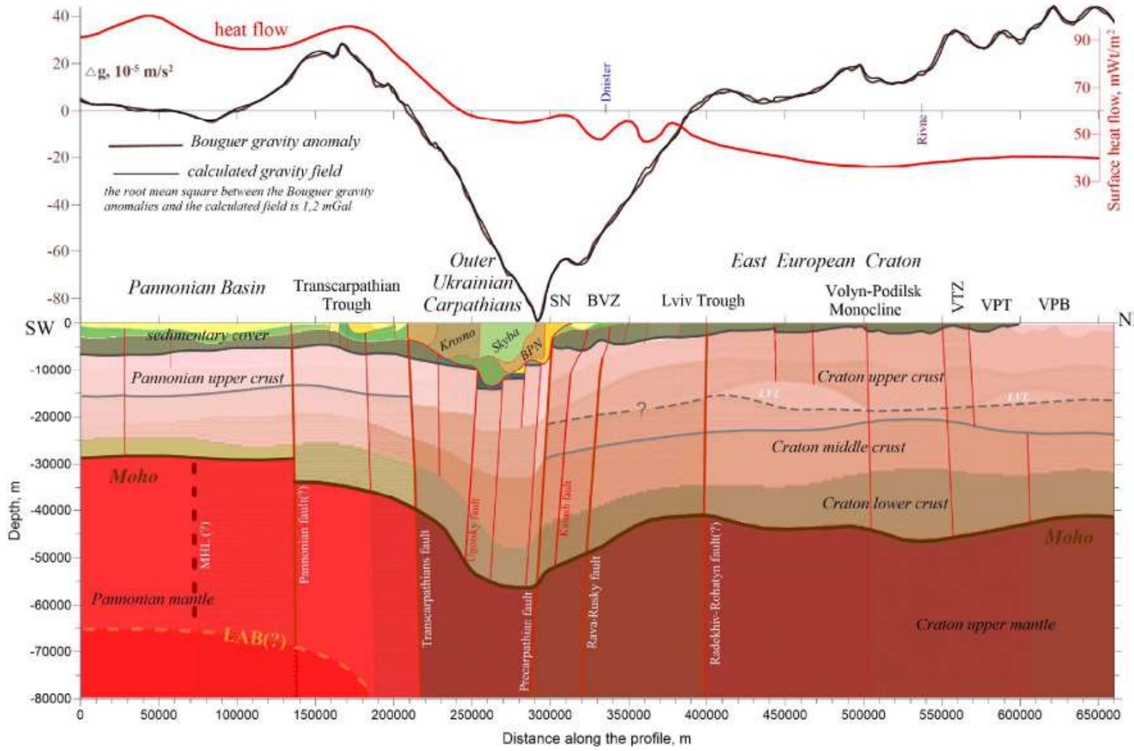

Fig. 12. Tectonic interpretation of the Density model along the PANCAKE profile

The gray thick line is a conditional boundary between the upper and middle crust. Other symbols: LVL – low velocity layer [Starostenko et al., 2013]; MHL – Mid Hungarian Line – probable boundary between the Tisza-Dacia and ALCAPA terrains; LAB – lithosphere-asthenosphere boundary below the Pannonian Basin [Horváth, 1993; Verpakhovska et al., 2018]. Other explanation as in Fig. 8

The ancient flysch-molasse accretionary prism, to which the Flysch Carpathians belong, was formed by the convergence of the Late-Alpine ALCAPA, TISZA-DACIA terranes with Eurasia [Csontos & Vörös, 2004] and the subduction of the Carpathian basin (sub)oceanic crust under these terranes [Hnylko, 2011]. On the other hand, one of the main features of WARR research in the Western Carpathians based on seismic profiles of the CELEBRATION 2000 experiment [Grad et al., 2006; Janik et al., 2009; Guterch et al., 2015, etc.] and PANCAKE [Verpakhovska et al., 2018] is the detection of inclined seismic boundaries in the upper mantle, which dip in the north and northeast direction, opposite to the southwest direction of the Miocene subduction. These inclined seismic boundaries in the upper mantle are interpreted as modern collision and subthrust (intrusion) of terranes or their marginal segments under the Craton. In density models of the Earth's crust and upper mantle in the OUC and EEC joint zone, it is very difficult to predict the extension nature of the main deep faults into the upper mantle. But, if you pay attention to the MOHO geometry, then the slope of its deepening in the OUC zone in the northeast direction along the PANCAKE profile, which was determined by gravity modeling, in our opinion, is consistent with views about modern subduction.

The above-mentioned longitudinal seismic profile of RP-VI is located southwest of the Carpathian gravity minimum axis at a distance of 5–6 km (see Fig. 3). On it, the MOHO boundary at intersection with the PANCAKE profile is marked at depths of 52–56 km [Zayats, 2013], so the MOHO depths under the OUC in the PANCAKE profile extension zone are probably not smaller. An important argument in favor of such depths (about 55 km) is the simulated MOHO according to the Airy – Heiskanen theory, as an isostatic compensation surface. According to this model, under the Transcarpathian Trough, the MOHO lies at a depth of 27–30 km, which increases sharply in the Transcarpathian fault zone; for the Folded Carpathians its depth is predicted to be within 55–65 km, for the EEC – 40–48 km (Fig. 13).

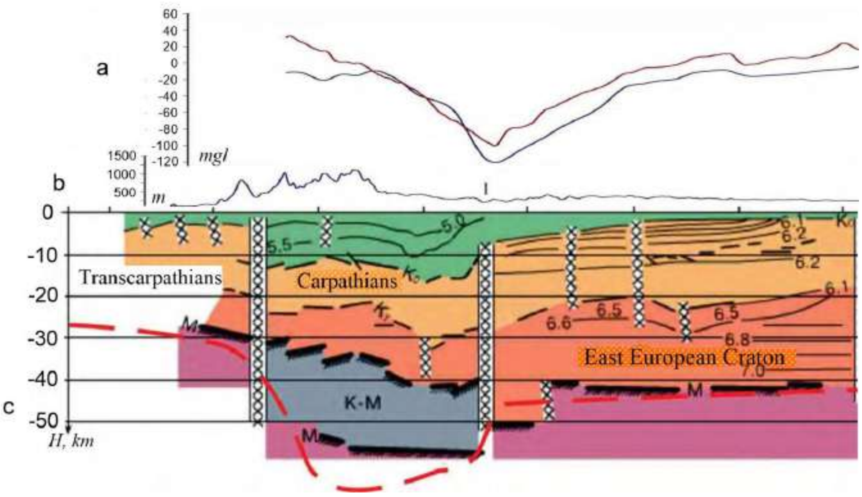

Fig. 13. Simulated values of the MOHO boundary according to the Airy – Heiskanen model (thick red dashed line) on the Earth's crust model along Geotraverse II (after Marchenko & Maksymchuk, 2013)

On the graphs: a – Bouguer anomalies (brown line) and isostatic anomalies (black line); b – topography according to the ETOPO1 model. In cross-section (c): 6.0 – velocities of seismic waves, K_0, K_1 – basement surfaces; M – MOHO boundary; K-M – crust-mantle layer

In the review of geophysical models of the lithosphere of Europe [Artemieva et al., 2006], based on a number of CELEBRATION 2000 seismic profiles, are given the crust depth intervals for the main tectonic units, in particular the Pannonian Basin – 25–30 km, OUC – 32–60 km, EEC – 38–52 km. We used these data to estimate the depths of MOHO in the PANCAKE density model. Separately, we will dwell on the gravimetric justification of its depth of 55–56 km under the OUC. In the zone of intersection of the OUC with the PANCAKE profile, the known Carpathian gravity minimum is close to its extreme value (-101×10^{-5} m/s^2). This indicates a probable increase in the MOHO depth under the OUC compared to the obtained depths in the Western Carpathians. The sublatitude seismic profile CEL12 is located at a distance of about 10 km from the Carpathian Foredeep and ends on the transverse profile CEL11 in the closest place to the territory of Ukraine (see Fig. 1). In the seismic model of the Earth's crust and upper mantle along the CEL12 profile, the MOHO depth reaches 38–40 km, along the CEL11 profile – 42 km. According to the MOHO depth map, when approaching the Ukraine border, it tends to deepen (it reaches more than 42 km) [Janik et al, 2009; Janik et al., 2011]. In this zone, the Carpathian gravity minimum is just beginning to manifest itself [Bielik et al, 2004]; its intensity here is about -70×10^{-5} m/s^2, and according to the PANCAKE profile it reaches -90×10^{-5} m/s^2. From a comparison of the MOHO depth map [Janik et al, 2011] and the Bouguer anomalies map [Bielik et al, 2006]: southeast of Warsaw, MOHO depths reach 52 km, and the intensity of the northern branch of the Carpathian gravity minimum (LL zone – Lublin Low) reaches only -60×10^{-5} m/s^2. Therefore, in the area where the PANCAKE profile crosses the gravitational minimum, the depth of the MOHO may well be around 54–56 km.

The density model within the EEC. The density of the lower crust (3.10×10^3 kg/m^3) and the upper mantle (about $3.29–3.32\times10^3$ kg/m^3) are consistent with the data [Tašárová et al., 2016]. The geometry of the EEC Earth's crust generally falls within the limits of tectonic interpretation [Verpakhovska et al., 2018].

The interpretation of the low-velocity zones (lenses) (LVL) identified in the seismic model [Starostenko et al., 2013], and therefore the low densities zones, is ambiguous. According to the authors of the work [Verpakhovska et al., 2018], these may be zones of weakening, in any case, partially under the influence of the thrust Paleozoic complexes of the West European Platform on the EEC.

About the crust-mantle transition zone. The transition zone under the Carpathians in the tectonic interpretation of the seismic model along the PANCAKE profile (Fig. 6), unlike the seismic model along the Geotraverse II (Fig. 8), is absent. In the density model, averaged density values were chosen for the lower crust and upper mantle, which take into account the possible influence of the crust-mantle substrate. The inclusion in the density model of the transition zone under the Pannonian basin and under the EEC (according to [Verpakhovska et al., 2018]) will lead to a rise of the crust-mantle surface and, possibly, to an increase of the density values for upper mantle or crust, i.e. it requires additional model studies.

About the Lithosphere-Asthenosphere Boundary (LAB) depths. According to a number of CELEBRATION 2000 seismic profiles in the ALCAPA-Carpathians area, the depths of LAB are determined in the range of 75–100 km (after [Artemieva, 2019]). According to the 3D LitMod model [Tašárová et al., 2016], under the Pannonian Basin in the part adjacent to the Transcarpathian Trough, the LAB depths range from 90 km to 100 km. In the article [Starostenko et al., 2013] for this region based on the materials [Artemieva et al., 2006; Horváth, 1993; Kutas, 1993] for LAB, a depth of 60–70 km is indicated; in the tectonic interpretation [Verpakhovska et al., 2018] data [Horváth, 1993] – 65 km were used. That is, the question of the thickness of the lithosphere under the Pannonian basin is debatable today. Within the ALCAPA the asthenosphere density is estimated at $3.30{\times}10^3$ kg/m^3 [Tašárová et al., 2016], which is close to the mantle density. In the models [Grabowska, et al., 2011], the density of the asthenosphere is $3.33{\times}10^3$ kg/m^3, and the density of the mantle is higher – $3.37{\times}10^3$ kg/m^3. According to the CEL09 profile [Godová et al., 2021], the depth of the LAB is 90 km, the density of the asthenosphere is $3.27{\times}10^3$ kg/m^3, and the density of the mantle is $3.30{\times}10^3$ kg/m^3. Taking into account the boundary of the LAB requires additional research on the depth of its occurrence and estimation of the density of the asthenosphere. Therefore, in the tectonic interpretation of the density model, the LAB depth of 65 km is only indicated.

Conclusions

The article describes the geological and tectonic analysis of the Bouguer gravity anomalies and presents the 2D density model of the cross-section of the Earth's crust and upper mantle of the Ukrainian Carpathians, adjacent Troughs and the southwestern slope of the East European Craton along the PANCAKE seismic profile.

The final results are the following.

1. The simulation results confirm the difference in the structure of the Earth's crust and upper mantle of the ALCAPA lithospheric plate and the Precambrian Craton. The ALCAPA plate is younger, characterized by a small thickness and low density of the Earth's crust. The density of the upper mantle under this plate is also lower ($3.20–3.21{\times}10^3$ kg/m^3) compared to the upper mantle under the Outer Ukrainian Carpathians and the East European Craton ($3.28–3.30{\times}10^3$ kg/m^3), which may be related to a change in composition and increased heat flow under ALCAPA.
2. The Ukrainian fragment of the East European craton in the extension zone of the PANCAKE profile is characterized by a typical thickness of the crust (~41–45 km). The upper part of the crystalline crust, in contrast to the middle part ($2.86–2.90{\times}10^3$ kg/m^3) and the lower part ($2.98–3.10{\times}10^3$ kg/m^3), is characterized by a lower density and greater differentiation in the horizontal direction and with depth (from $2.66{\times}10^3$ kg/m^3 to $2.86{\times}10^3$ kg/m^3).
3. The complex transition zone (subduction zone, Carpathian Orogen) between the ALCAPA microplate and the East European Craton causes an intense negative the Bouguer anomaly – the Carpathian gravity minimum, which reaches $-90{\times}10^{-5}$ m/s^2.
4. The Carpathian gravity minimum has a complex nature: rocks of the Neogene and Paleogene-Cretaceous flysch of the Boryslav-Pokuttia nappe with low density ($\leq 2.50{\times}10^3$ kg/m^3), the main huge discharge of the Precarpathian fault (≥4 km), which on the extreme southwestern slope of the platform (relatively local factors), significant deepening of the MOHO under the Carpathian edifice (regional factor).
5. According to our density model, the MOHO depth under the front of the Ukrainian Carpathian Thrust reaches 56 km.
6. Research based on the interpretation of the anomalous gravity field using data from seismic methods made it possible to build a geodensity model of the Earth's crust along the PANCAKE regional profile.
7. The results of the research confirmed the main features of the structure of the Earth's crust, and also allowed us to obtain new data on the depth of occurrence and the morphology of the MOHO boundary along the PANCAKE profile.
8. The conducted studies once again confirm that geo-density (gravity) modeling is an effective tool and a necessary component in the construction of complex geophysical models of the Earth's crust and upper mantle.

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ГУСТИННА МОДЕЛЬ ЗЕМНОЇ КОРИ УКРАЇНСЬКИХ КАРПАТ ПО ПРОФІЛЮ PANCAKE

Цілі роботи – аналіз та геолого-тектонічна інтерпретація аномального гравітаційного поля Українських Карпат та прилеглих територій, побудова густинної моделі земної кори та верхньої мантії по міжнародному сейсмічному профілю PANCAKE. Потреба побудови густинної моделі вздовж профілю PANCAKE зумовлена значним інтересом широких кіл геологів та геофізиків до результатів сейсмічних досліджень щодо цього профілю, а також певними розбіжностями у сейсмологічних моделях різних авторів. Методика гравітаційного моделювання, використана в роботі, передбачає аналіз геолого-геофізичних карт та моделей, які стосуються геолого-тектонічної будови регіону досліджень, створення початкової структурної частини моделі та визначення густин товщ та блоків моделі. Геометрію та густини моделі уточнено методом підбору, який ґрунтується на інтерактивному розв'язанні прямої задачі гравіметрії та аналізі причин невідповідності розрахованого поля сили тяжіння і аномалій Буге. Методами гравітаційного моделювання досягнуто якісної відповідності густинної моделі тектонічній інтерпретації сейсмічного розрізу уздовж профілю PANCAKE. Результати моделювання підтверджують чотиришарову будову земної кори: осадовий покрив, верхня, середня та нижня частини кори, які суттєво різняться густиною, а також відмінність у будові земної кори та верхньої мантії літосферної плити ALCAPA, Флішових Карпат та докембрійського кратона. Плита ALCAPA характеризується малою товщиною (до 29 км) та низькою густиною земної кори. Густина верхньої мантії ALCAPA менша (3,20–3,21·10^3 кг/м^3) порівняно з верхньою мантією під Українськими Карпатами та Східноєвропейським кратоном (3,28–3,30·10^3 кг/м^3), що може бути пов'язано зі зміною складу та підвищеним тепловим потоком під ALCAPA. Український фрагмент Східноєвропейського кратона у зоні простягання профілю PANCAKE характеризується типовою товщиною кори (~41–45 км). Верхня частина кристалічної кори, на відміну від середньої (2,86–2,90·10^3 кг/м^3) і нижньої частин (2,98–3,10·10^3 кг/м^3), характеризується меншою густиною і більшою диференціацією у горизонтальному напрямку та із глибиною (від 2,66·10^3 кг/м^3 до 2,86·10^3 кг/м^3). Складна перехідна зона (зона субдукції, Карпатський ороген) між мікроплитою ALCAPA та Східноєвропейським кратоном спричиняє інтенсивну від'ємну аномалію гравітаційного поля – Карпатський гравітаційний мінімум, який сягає –90·10^{-5} м/с^2. Його природа комплексна: розущільнені породи неогену та палеоген-крейдовий фліш (≤2,50·10^3 кг/м^3) Бориславсько-Покутського покриву, основний величезний скид Передкарпатського розлому (>4 км) на крайньому південно-західному схилі платформи (порівняно локальні фактори) та істотне заглиблення поверхні МОХО під Карпатською спорудою (регіональний фактор). Глибина залягання границі МОХО під фронтом Карпатського насуву за нашою густинною моделлю сягає 56 км.

Ключові слова: Українські Карпати; земна кора; верхня мантія; поверхня МОХО; гравітаційні аномалії; сейсмічна модель; гравітаційне моделювання; густинна модель.

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