Geological and tectonic interpretation of the new Bouguer gravity anomaly map of Slovakia

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Abstract: This paper analyzes the latest complete Bouguer gravity anomaly map of Slovakia in relation to geological architecture. The observed gravity field consists of regional and local gravity anomalies, as well as marked horizontal gravity gradients. The most remarkable regional feature on this map is the large field with low-density masses in the northern part of Central Slovakia (the so-called Western Carpathian gravity low), which is divided into two gravity sub-lows: the Outer and Inner Western Carpathian gravity low. The source of the first sub-low is the sediments of the Outer Western Carpathian flysch units, and the second one is a crust with prevailing granites and orthogneisses. It is suggested that this field is only the torso of the original one, which stretched along the entire length of Slovakia from the SW to the NE. However, in the youngest stages of tectonic development, the negative gravity anomalous field in the territory of West and East Slovakia changed to a positive one due to the thinning of the lithosphere and crust by the influence of asthenolithic masses from the mantle. The higher density masses in Central Slovakia south of the Carpathian gravity low are not caused only by asthenolithic action. The different tectonic segment with a predominance of metamorphic complexes and a higher average density, in comparison to the low-density granitized complexes in the north, also contributes to its manifestation. The boundary between these two segments in Central Slovakia is a linear and sharp tectonic zone and coincides with the extensive Pohorelá shear zone. Several local anomalies also occur on the complete Bouguer anomaly map, and they were also subjected to geological analysis. These include local areas with a predominance of heavier crust, such as the core mountains in western Slovakia, subvolcanic intrusions, metabasic complexes, and the Cadomian basements. Prominent horizontal gravity gradients reflect the tectonic interfaces (faults, shear zones) that originated mainly during the youngest period of the Western Carpathian tectonic development and were also interpreted. The faults shown in the complete Bouguer anomaly map were active mainly during the transpressional and extensional stage of the Neo-Alpine tectonic development.

Keywords: Slovakia, Western Carpathians, complete Bouguer gravity anomalies, geology, tectonics

Introduction

Gravimetric research has a long tradition in Slovakia. The first documented gravimetric measurements were related to the search for oil and gas and were performed by Lóránd Eötvös and his co-workers between 1915–1916 in the Vienna Basin and later by the company European Gas et Electric co. between 1936–1938 in the Danube Basin (Grand et al. 2001). The first systematic regional gravimetric mapping of the entire territory of Czechoslovakia at 1:200,000 scale with an average point density of 1 point/5 km^2 was carried out at the beginning of the 1960s (Ibrmajer 1963). The most important regional survey at 1:25,000 scale was performed by Geofyzika Brno between 1956 and 1992. Different types of relative gravity meters were used during this enormous project, such as GAK PT, Worden, Canadian CG-2, and Scintrex CG-3M. The total number of measured points was 212,478, which represents a very high point density of 3–6 points/km^2. This gravity database became a high-quality material for the calculation of the first important versions of gravity anomaly maps and their interpretations (Šefara et al. 1987). The next improvement of the national Slovak regional gravity database was carried out in the frame of the Atlas project of geophysical maps and profiles (Grand et al. in Kubeš et al. 2001), which was mainly focused on the unification of the computation of terrain corrections. The recalculated complete Bouguer anomaly map (CBA) from this project also became a part of the map of the Central Europe region in the scope of the CELEBRATION 2000 project (Bielik et al. 2006). In the frame of the research project APVV "Bouguer anomalies of new generation and the gravimetrical model of Western Carpathians", all available gravity data in Slovakia, mainly from the archive of Geocomplex, Co Ltd. (Szalaiová et al. 2012), were integrated into one unified gravimetric database. The existing regional gravity database was supplemented with 107,437 detailed gravity points (Zahorec et al. 2017b). Particularly important was a new generation of the improvement of terrain corrections computations with the use of a new software solution (program Toposk, Zahorec et al. 2017a) and the incorporation of current detailed digital elevation models, e.g., DMR3 (https://www.geoportal.sk/sk/zbgis/udaje-zbgis/aktualizacia-dmr-3-5.html). This new version of the gravity database of the Slovak Republic became a part of a unique CBA map from Central Europe and partly from Western Europe within the AlpArray project (Zahorec et al. 2021).

The compilation and publication of a new CBA map of Slovakia (Pašteka et al. 2017) has been a significant contribution to the geological and tectonic interpretation of gravity fields in recent years. This map shows several remarkable structures that reflect the geological architecture. Back when it was published, the authors had written the following in the introduction: "*the resultant CBA field represents very important material for the interpretation of the structure, composition, and tectonics of the Western Carpathians within our territory*". Therefore, the aim of this work is precisely the above – the geological interpretation of gravity anomalies and horizontal gradients based on the latest knowledge about the geology and tectonics of the Western Carpathians. The interpretations also take into account the results of other geophysical methods (e.g., magnetotelluric, magnetic, seismic, and geothermic). We also benefited from previously-published geophysical studies of other crustal and mantle parameters, such as electrical conductivity, thermal fields in Slovakia, etc. (e.g., Fusán et al. 1971, 1979; Plančár 1980), as well as from results of the APVV projects THERMES (e.g., Majcin et al. 2016, 2017; Bezák & Majcin 2018) and LITHORES (Vozár et al. 2022).

Therefore, we will focus on geological interpretation of the most striking structures in the CBA map:

- The Western Carpathian gravity low (WCGL), which was already interpreted in the past by Tomek et al. (1979) and Pospíšil & Filo (1980); however, the questions of what the real source of the WCGL is and why it does not continue further to the SW and NE have not yet been answered.
- Significant local gravity anomalies.
- Prominent horizontal gradients in gravity which reflect the lineaments, which are of tectonic origin.

Geological setting

The Western Carpathians (WECA) Mountain range dominates on the territory of Slovakia (Fig. 1). It is tectonically divided (e.g., Bezák et al. 2004) into the Outer Western Carpathians (OWECA), formed by the Flysch belt (FB), and the Inner Western Carpathians (IWECA).

The IWECA segment consists of the major Paleo-Alpine crustal tectonic units of the Tatricum, Veporicum, Gemericum, and Zemplinicum, as well as the superficial Mesozoic nappes. Crustal tectonic units are composed of Hercynian crystalline complexes (Proterozoic and Paleozoic) and Mesozoic cover units. The crystalline complexes represent the fundament of the entire crust and have a varied lithological composition. These complexes were originally middle crustal Hercynian nappes (Bezák et al. 1997b). They are composed of metamorphic units of various degrees of metamorphism intruded by granitoids.

The youngest tectonic stage (Neo-Alpine) was driven by a successive subduction of the Outer flysch basin ocean floor. Progress of IWECA units over subducting slab was realized by the movement of individualized crustal segments (terranes) and resulted in an oblique collision of the IWECA block with the European platform (EP) and formation of the flysch nappes accretionary wedge. The oblique character of the collision forced the disintegration of IWECA into several separate crustal segments with different geological compositions. These crustal blocks, which had been separated by strike-slip tectonic boundaries, moved during the occupation of the EP oceanic embayment independently. As a result, they allowed the juxtaposition of formerly distant parts of segments with contrasting geology compositions and varying physical properties, which are reflected in the individual geophysical models on the profiles (e.g., magnetotelluric, lastly Vozár et al. 2021), and on the maps (e.g., CBA map, magnetic map after Kubeš et al. 2010).

Except for the external Flysch belt, as well as the Danube and East Slovak basins, the Western Carpathian Mountain range is not geomorphologically uniform – it is rather a series of smaller mountain ranges (horsts) and basins (grabens). This is a consequence of the youngest stages of Neo-Alpine tectonic evolution, which was accompanied by the influence of ascending asthenolith and related massive volcanism. The horsts contain Pre-Tertiary basement complexes, and the grabens are filled with Tertiary sediments.

Geophysical setting

Many works have been devoted to the seismic and seismological research of the Western Carpathians. Some of the most important we can mention are, for example, the papers: Beránek & Zátopek (1981), Babuška et al. (1987), Tomek et al. (1987, 1989), Vozár et al. (1999), Grad et al. (2006), Środa et al. (2006), Plomerová & Babuška (2010), Janik et al. (2011), Brixová et al. (2018a, b).

The publications of Tomek et al. (1979), Pospíšil (1980), Pospíšil & Filo (1980), Šefara et al. (1987, 1996, 1998), Bielik (1988a, b, 1999), Bielik et al. (1994, 2004, 2006, 2022), Lillie et al. (1994), Bezák et al. (1995, 1997a), Zeyen et al. (2002), Dérerová et al. (2006), Alasonati Tašárová et al. (2009, 2016), Grabowska et al. (2011), Grinč et al. (2013); Šamajová et al. (2019) brought important gravimetric knowledge about the structure and tectonics of the Western Carpathians.

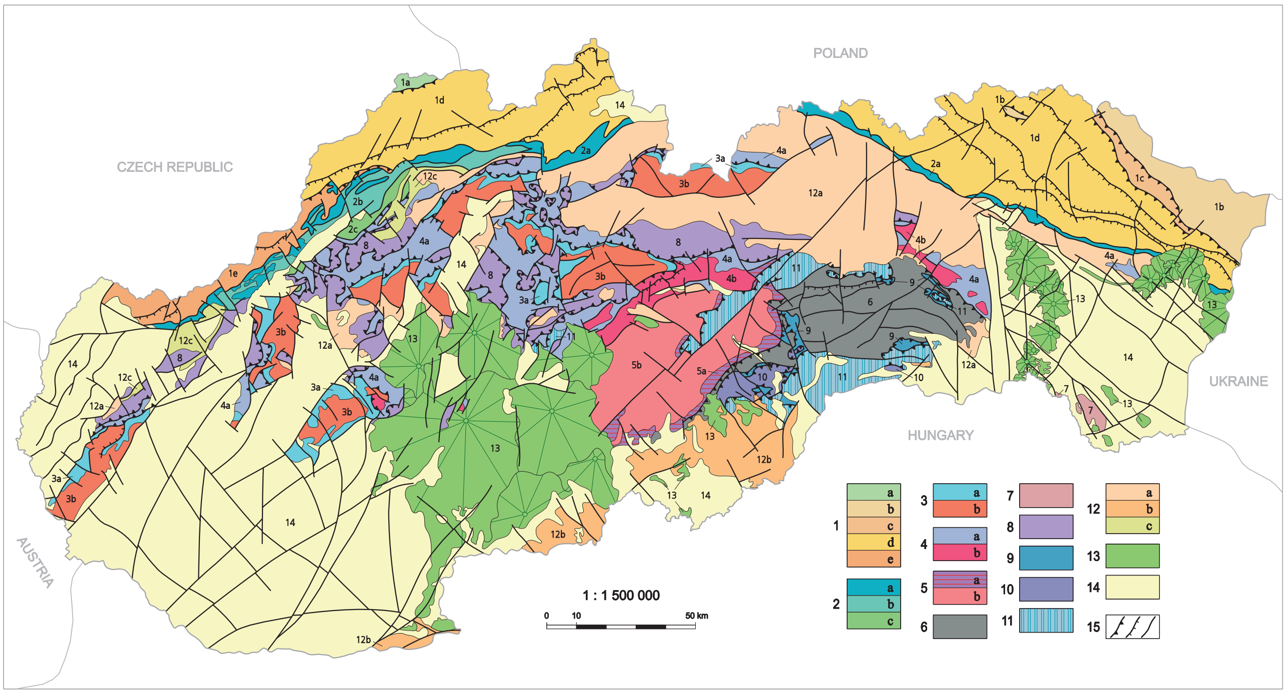

Fig. 1. Simplified geological map of Slovakia (Bezák et al. 2011, according to the General geological map of the Slovak Republic 1:200,000, Bezák et al. 2008). Neo-Alpine tectonic units of the Outer Carpathians: 1 – Flysch Belt: a = Silesian Nappe, b = Dukla Unit and Smilno tectonic inlier, c = Miková–Snina Zone, d = Magura group of nappes, e = group of Biele Karpaty nappes; 2 – Klippen Belt s.l.: a = Klippen Belt s.s. undivided, b = Klape tectonic unit, c = Manín and Haligovce tectonic units; Paleo-Alpine tectonic units of the Inner Western Carpathians: 3 – Tatricum: a = mostly Mesozoic and Late Paleozoic formations, b = crystalline complexes; 4 – Fatricum and northern Veporicum: a = Mesozoic and Late Paleozoic formations, b = crystalline complexes; 5 – southern Veporicum: a = Mesozoic and Late Paleozoic formations, b = crystalline complexes; 6 – Gemericum; 7 – Zemplinicum; 8 – Hronicum; 9 – Meliaticum; 10 – Turnaicum; 11 – Silicicum; formation superimposed over the nappe structure: 12 – sedimentary basins with Paleogene and Late Cretaceous fill: a = Inner Carpathian Paleogene basin, b = Buda Basin, c = Late Cretaceous and Paleogene deposits; 13 – Neogene and Quaternary volcanics; 14 – Neogene and Quaternary deposits; tectonic boundaries; 15: from left to right – main Alpine thrusts, other overthrust lines, unspecified faults.

The interpretation of the magnetic field of Slovakia was elaborated, for example, in the papers of Kubeš et al. (2001, 2010) and Rozimant et al. (2009).

Several different geophysical studies have also described other parameters of crustal and mantle structures like electrical conductivity or its thermal state in Slovakia. The conductivity parameters of the Western Carpathians are based on the magnetotelluric (MT) method and the resulting conductivity models, which were integrated with information from previous seismic and gravimetric results along profiles MT15 and 2T and presented in Bezák et al. (2014, 2020) and Vozár et al. (2021, 2022). The work of Majcin et al. (2018) was focused on the conductivity MT modeling of the contact of the Outer Carpathian flysch, the Klippen Belt and the Inner West Carpathian Paleogene near Stará Ľubovňa. The knowledge of the thermal state of the lithosphere in the region of Slovakia is based on the publication for direct approaches as the Geothermal Energy Atlas of Slovakia (Franko et al. 1995). The geothermal studies are mainly represented by the results of stationary methods applied to sections passing across the Carpathian arc and non-stationary 2D and 3D models (Majcin 1993; Majcin & Tsvyashchenko 1994; Majcin & Dudášová 1995; Majcin et al. 1998, 2015).

Methods

As we have previously mentioned in the Introduction, the current gravity database of Slovakia consists of almost 320,000 points, for which the most important corrections were recalculated and improved. A detailed description of all individual reprocessing steps is given in Zahorec et al. (2017b).

The complex geological structure of the Western Carpathians is a result of accumulation of various tectonic segments during the long-lasting tectonic development. This collage of fragments is also reflected in the diversity of the observed gravity and other geophysical data.

Our interpretation of the gravity field was based on the latest knowledge of the geological structure of the territory of Slovakia (the General geological map of Slovakia 1:200,000 being the main source) and the geological–geophysical models of tectonic development, mainly in the Neo-Alpine period (Tomek et al. 1979, 1987, 1989; Royden et al. 1982; Doglioni et al. 1991; Ratschbacher et al. 1991a, b; Csontos et al. 1992; Royden 1993; Bielik et al. 1994, 2004, 2006; Bezák et al. 1995, 2020; Doglioni 1995; Fodor 1995; Nemčok et al. 1998; Vass 1998; Bielik 1999; Fodor et al. 1999; Golonka et al. 2006; Marko et al. 2017, 2021). When analyzing the fault lineaments, we rely on the structures expressed in the Tectonic Map of Slovakia (Bezák et al. 2004), as well as on other publications with a structural focus (e.g., Marko et al. 2017, 2022).

One very important source of information was the specific density of the main groups of rocks (Stránska et al. 1986; Šamajová & Hók 2018) and the geological cross-sections from regional geological maps, which we extrapolated to the greatest possible depth – at certain places up to the Moho discontinuity, thanks to deep-range geophysical data. These geological cross-sections were confronted with the results of geophysical measurements of the profiles (mainly magnetotelluric, seismic, and gravimetric). We created integrated models, such as those we used, for example, in the interpretation of the lithospheric structure (Bezák et al. 1997a; Zeyen et al. 2002; Dérerová et al. 2006; Grinč et al. 2013; Alasonati Tašárová et al. 2016; Šimonová et al. 2019). In recent years, we have benefited mainly from the MT method (e.g., Bezák et al. 2014; Majcin et al. 2018) and gravimetric (Dérerová et al. 2021) measurements in several profiles.

Geological interpretation of the CBA map

The CBA map consists of the large regional gravity anomalies, local gravity anomalies, and horizontal gravity gradients.

Regional gravity anomalies

The regional gravity anomalies reflect deep-seated, larger-scale, anomalous sources. On the CBA map, the most remarkable of them is a large negative gravity zone (field A1, A2 in Fig. 2), which is caused by the low-density masses building up the northern parts of Central Slovakia. Here, Tomek et al. (1979) firstly defined the so-called Western Carpathian gravity low (WCGL), as one of the most important gravity anomalies in the Carpathian Mts. From the south, it is sharply separated from the segment characterized by positive gravity values (field B).

In the past, the source of the WCGL was interpreted by Tomek et al. (1979) as unusually shallow (maximum lower boundary of this source reaches a depth of 8.5 km). However, this interpretation was soon challenged by Pospíšil & Filo (1980), who interpreted the WCGL as an effect of granitic and flysch complexes. The more realistic interpretation (Bielik et al. 2022) is that the WCGL represents the effects of the Tatric complexes of granitic character (field A2, Fig. 2) and, in the northernmost part, the effect of flysch sediments and Foredeep (field A1). Therefore, Bielik et al. (2022) divided the WCGL into two gravity sub-lows: the Outer Western Carpathian gravity low (OWCGL – A1) and the Inner Western Carpathian gravity low (IWCGL – A2).

The nappes of flysch sediments in this area moved over the European Platform (EP) and suppressed the effects of the higher-density masses of the EP. The EP complexes with a high content of metabasites also cause a magnetic anomaly (Kubeš et al. 2010). South of the Carpathian Conductivity Zone (CCZ), which forms the border of the EP, the structure of the crust is dominated by complexes of a granitoid character (granitoids, orthogneisses, migmatites), which are part of the Tatricum unit, but also the northern part of the Northern Veporicum unit (the Ľubietová zone), which is also part of the WCGL.

The granitoid Tatricum complexes similar in the northern part of Central Slovakia also appear in the geological structure of the Tatricum unit in Western Slovakia. The question is, why they do not exhibit the same gravity effect? The most likely explanation is that it is due to the action of young ascending asthenolithic masses from the mantle (Babuška et al. 1987, 1988) and thinning of the lithosphere (~100 km, Dérerová et al. 2006) and crust (only 25 km, Bielik et al. 2018; Šujan et al. 2021), which changed the gravity effect of the Tatricum western segment into the positive regional anomaly. The asthenolithic masses of the partially-melted lithosphere had moved closer to the surface. The exception is the Vienna basin, where the crust reaches the classic thickness of the continental crust (30–35 km, Bielik et al. 2018) and asthenolithic masses did not penetrate there. From the gravity field point of view, it thus forms the most southwestern part of the WCGL. The extent of influence of the asthenolithic masses (field C1) is shown in Fig. 2. It also corresponds with the area of higher values of the heat flow (Majcin et al. 2017), thinner crust (Bielik et al. 2018) – Fig. 3, and thinner lithosphere (Babuška et al. 1987, 1988; Zeyen et al. 2002; Majcin et al. 2015; Dérerová et al. 2020; Bielik et al. 2022).

A similar influence of asthenolithic masses in Western Slovakia (asthenolith C1, Fig.2) can be observed in the East Slovak segment as well (asthenolith C2, Fig. 2). This is most evident in the Outer flysch belt, which is even thicker than in Western Slovakia, however, the influence of its lower density masses is nevertheless not manifested. The entire territory is represented by the positive gravity values, which are probably due to the gravity effect of the higher-density masses. In Eastern Slovakia, the area of action of asthenolithic masses (Fig.2) coincides perfectly with the area of increased heat flow (Fig. 3) and shallow Moho (25 km, Majcin & Tsvyashchenko 1994; Bielik et al. 2018; Šujan et al. 2021). Moreover, the thick conductive zones in the middle crust are clearly visible in the deep MT image of Eastern Slovakia and are probably the result of the existence of the shallow upper mantle and asthenolithic masses over the course of the progressing subduction (Vozár et al. 2022).

The southern border of the WCGL in Central Slovakia is almost linear (see Fig. 2), very sharp, and very steep in the MT model along the 2T seismic profile (Vozár et al. 2021, Fig. 4). It was interpreted as an important tectonic ENE–WSW shear zone (strike slip) described by geophysicists as the Vepor deep-range fault (e.g., Procházková & Schenk 1986; Šefara et al. 1987). It coincides spatially with the Pohorelá shear zone, known before as the Pohorelá fault (Phf in Fig. 4). It also coincides with the sharp boundary between the non-conductive

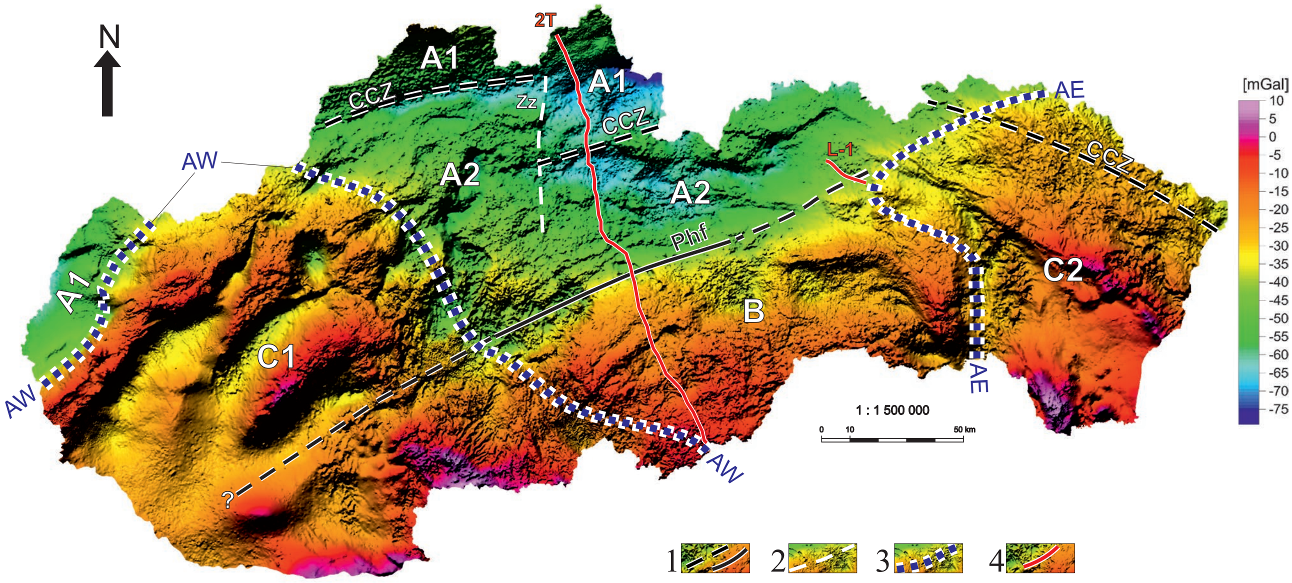

Fig. 2. Interpretation of main gravity anomalies in the territory of Slovakia (map of CBA anomalies after Pašteka et al. 2017). A – WCGL (A1 = Flysch part, A2 = granitic part); B – block of prevailing metamorphic complexes; C – territory of asthenolith influence and crustal thinning (C1 = western, C2 = eastern). 1 – important crustal boundaries (CCZ = Carpathian Conductive Zone, Phf = Pohorelá shear zone), 2 – Zázrivá tear fault (Zz), 3 – assumed asthenolith influence borders (AW = western asthenolith, AE = eastern asthenolith), 4 – MT profiles.

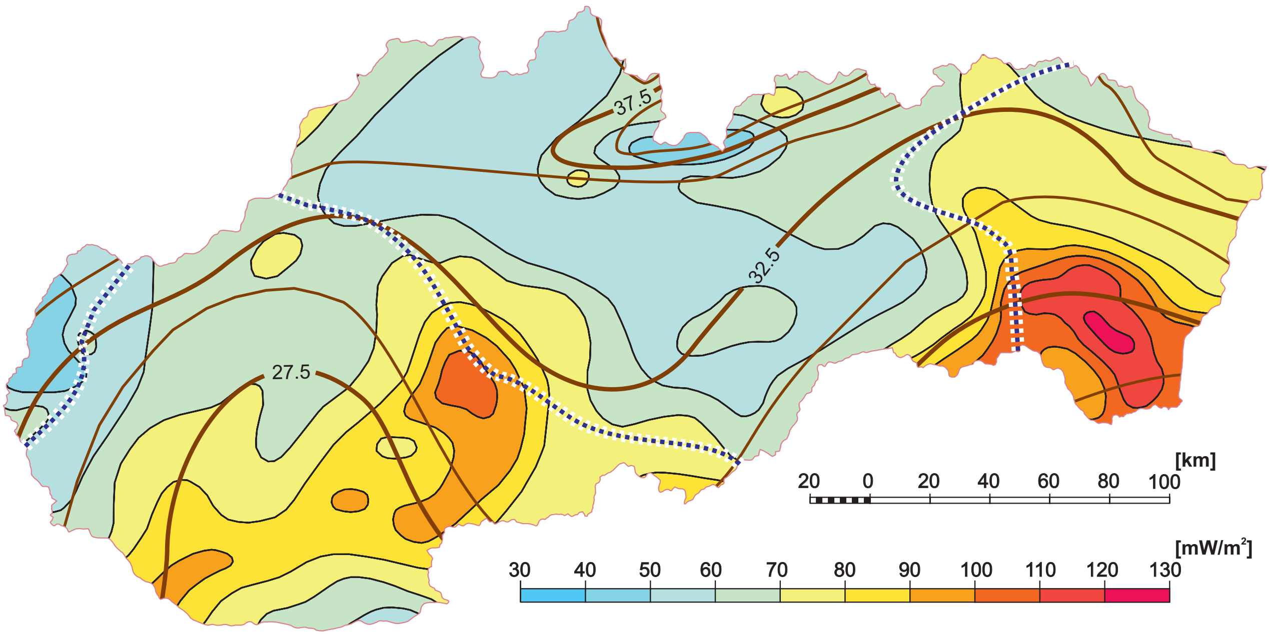

Fig. 3. Map of terrestrial heat flow density – black lines (modified from Majcin et al. 2017) and depth of Moho –dark brown lines (from Bielik et al. 2018). Dotted dark violet line– assumed border of asthenolith influence from Fig.2.

complexes in the north and the conductive complexes in the south in this MT model (Vozár et al. 2021). According to the current knowledge of the geological structure, these higher density complexes (field B) are mainly formed by the metamorphic complexes of the Hercynian tectonic units, which are different from the tectonic units presented below the WCGL. These are middle and lower gneissic and mica-schist Hercynian units according to Bezák et al. (1997b). In the current structure, they are also part of the crust that belongs to the Veporicum tectonic unit. In the NE part of WCGL, these higher density metamorphic units are partly covered by huge Inner Carpathian Paleogene sediments mainly in the Levočské vrchy Mts., and their interpretation is less clear. However, a short MT profile L-1 (Fig. 5), which was measured in this area, indicates a contact of the contrasting crust under Paleogene sediments (Fig. 5). It is interesting that this contact-tectonic boundary corresponds with the expected directional continuation of the Phf and possibly the Muráň line (the Maľcov segment).

Local gravity anomalies

The local gravity anomalies also represent an interesting phenomenon of the CBA map. Unlike the regional gravity anomalies, they reflect smaller-scale and near-surface anomalous sources. In this paper, only the most significant ones are interpreted (Fig. 6). The local gravity highs of the core

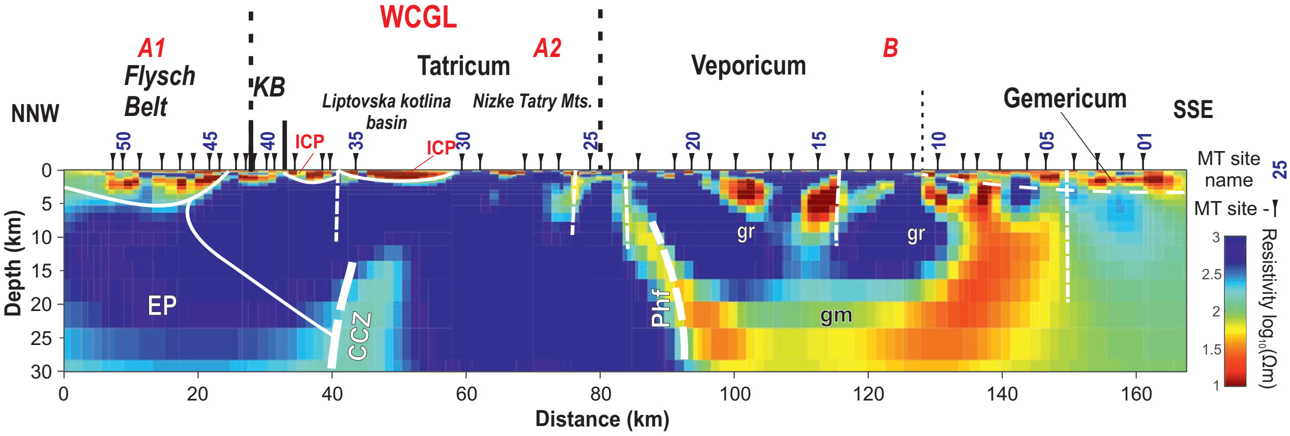

Fig. 4. 3D MT model section along seismic profile 2T (modified from Vozár et al. 2021). In the northern part, high-resistive granitic nature complexes of the Tatricum and the Ľubietová zone of the northern Veporicum (A2 in Fig. 2) dominate. In the northernmost part there are striking conductive Flysch units (A1 in Fig. 2). In the southern part (B, in Fig. 2), there dominate higher-conductive Veporic metamorphic complexes over granitoids. The boundary between the sectors A and B is marked by Phf. ICP=Inner Western Carpathian Paleogene sediments, gr=granites, gm=metamorfic complexes (prevailing gneisses and mica-schists).

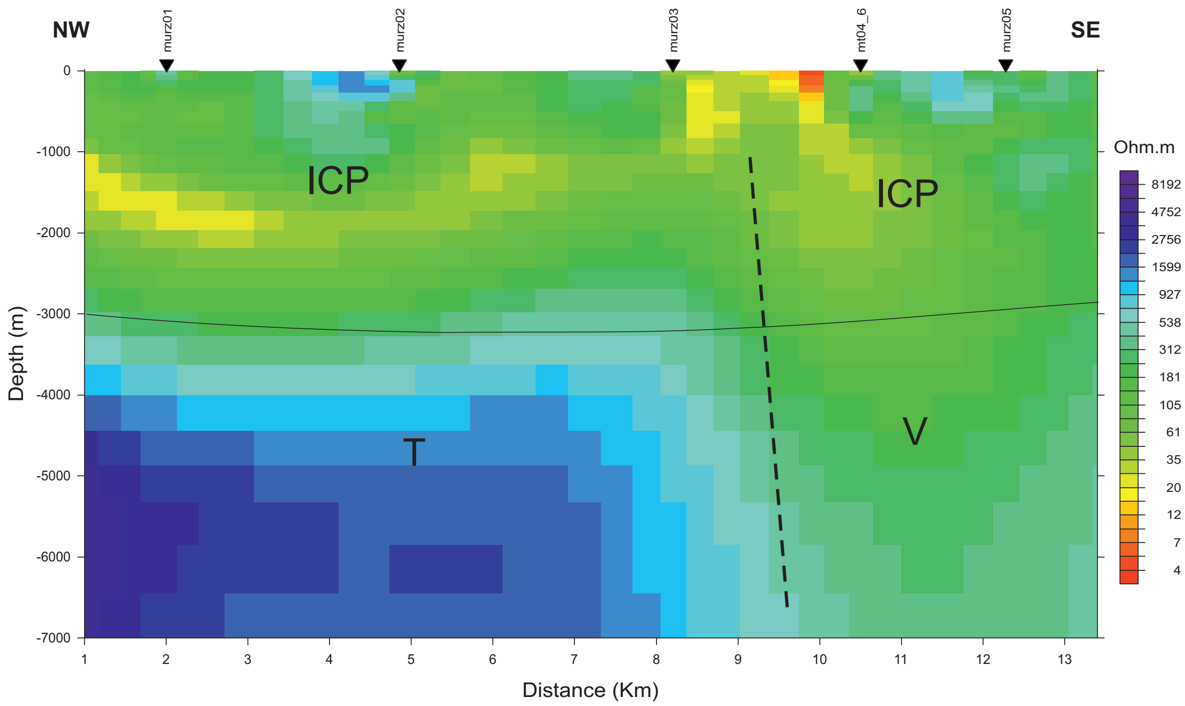

Fig. 5. The MT profile L-1 in the Levočské vrchy Mts. situated across the assumed crustal interface between the WCGL and the positive gravity segment in the southeast (see Fig. 2). A change in the conductivity character of the crust is visible in the substratum of the ICP sediments. ICP=Inner Western Carpathian Paleogene sediments, T=Tatricum and Northern Veporic Ľubietová zone, V=other Veporicum units.

mountains in Western Slovakia (i.e., the Small Carpathians, the Považský Inovec, the Tribeč Mts., numbers 1, 2, and 3 in Fig. 6, but also others which are less visible, such as the Strážovské vrchy, the Suchý and the Malá Magura Mts.) are among the most important. Their sources are the rocks that create these horsts, which are characterized by a higher density compared to the low-density of the sedimentary fill of the neighbouring grabens. The horsts were formed during the transpressional and later extensional Neo-Alpine processes. They had the same evolutionary origin without the presence of a subduction root. The basic process included disintegration of the moving crustal segments, uplift of the individualized horst blocks, and subsidence of the graben blocks, which was simultaneously filled with sediments from the eroded horst. The structure of the original crust, including the previously-mentioned core mountains, was the same throughout the entire area disturbed by the tectonic processes above. In general, it can be said that from the top to the bottom, this structure contained Mesozoic nappes and the Mesozoic cover of crystalline rocks, while below were the granitoids and orthogneisses of the upper Hercynian unit, which lay on the middle Hercynian gneiss unit and eventually on the lower, predominantly mica-schist unit. During the uplift of the horst, the uppermost units were eroded, including a large column of the granitoids, which represented the low-density complexes, and thus the high-density lower metamorphic units became dominant. The situation was inverse in the case of grabens: the granitoid layer was preserved, and its low-density gravity effect was additionally accentuated by the gravity effect of the accumulation of several kilometres thick of the Tertiary sediments. In the middle segment of the Western Carpathians, the contrast between the mountains and grabens is not significant (apart from the Liptovská kotlina Basin) due to the gravity effect of the thicker crust.

Other types of local anomalies are produced by the basic intrusive bodies in the crust. In Slovakia, they are represented by the Kollárovo gravity anomaly (No. 4 in Fig. 6), which has been interpreted several times in the past (e.g., Prutkin et al. 2011, 2014, and references therein). Similar anomalies can be found in Austria along the Rába line, as well as in Northern Hungary, the Eastern Slovak basin, and the Makó and Békés basins (Bielik et al. 2022).

The higher gravity values can also be caused by the Cadomian basement in the southern part of Slovakia. This is particularly manifested in the Pelsö unit (local anomaly No. 5, Fig. 6), and then in the southern part of Central Slovakia (the area of Fiľakovo, No. 7) where this basement also causes a significant magnetic anomaly (Kubeš et al. 2010). We also assume the effects of the Cadomian basement in the Zemplinicum (No. 11). The local increase in gravity values in Neovolcanic fields (anomaly No. 6 in Fig. 6) is caused by the elevation of the pre-Cenozoic basement with additional influence of the subvolcanic intrusions, which were interpreted on the MT profile MT-15 (Bezák et al. 2014).

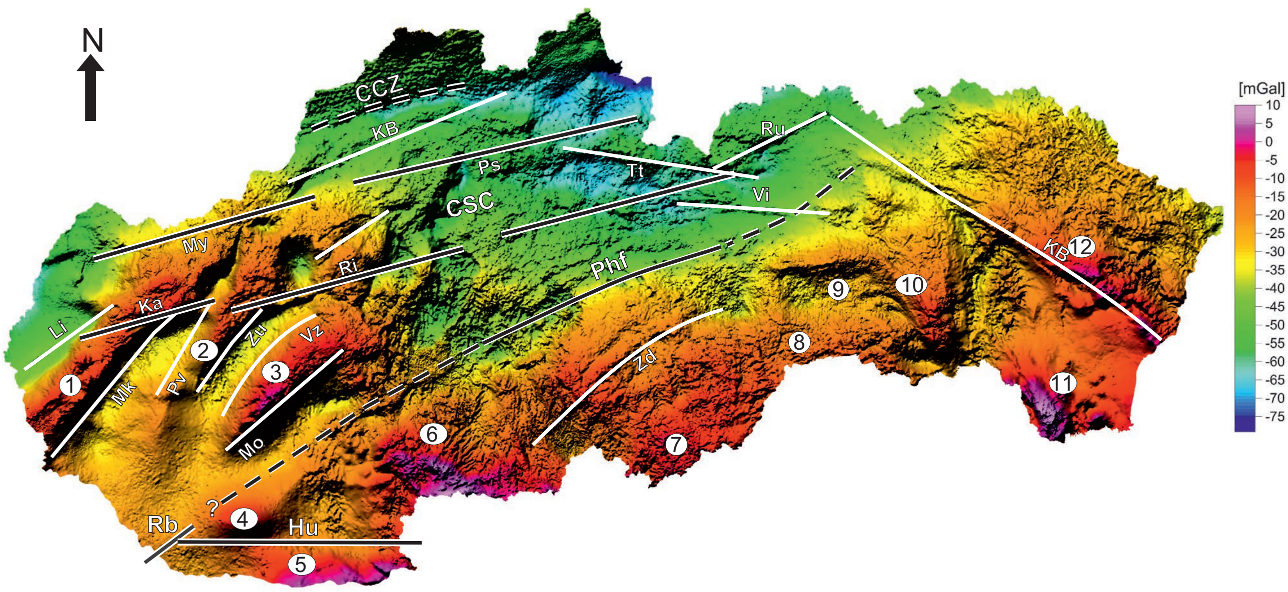

Fig. 6. Faults active during the transpressional stage of Neo-Alpine tectonic development and local gravity anomalies. Black lines: main transpressional shear zones: CSC – Carpathian shear corridor with individual faults (Ka = Kátlovce, My = Myjava, Ri = Rišňovce, Ps = Prosiek), CCZ – Carpathian conductive zone, Phf – Pohorelá shear zone, Hu – Hurbanovo fault, Rb – Rába fault. White lines: other transpressional faults (KB = Klippen Belt fault, Li = Leitha, Mk = Malé Karpaty, Pv = Považie, Zu = Závada-Dubodiel, Vz = Veľké Zálužie, Mo = Mojmírovce, Tt = Tatry, Vi = Vikartovce, Ru = Ružbachy, Zd = Zdychava. Faults according to the Tectonic map of SR, 2004. Numbers in circles: local gravity anomalies (1 – Malé Karpaty horst, 2 – Považský Inovec horst, 3 – Tribeč horst, 4 – Kolárovo, 5 – Pelso basement, 6 – pre-Cenozoic basement elevation and subvolcanic intrusions, 7 – southern Cadomian basement in southern Slovakia, 8 – Cadomian basement below Silicicum unit, 9 – Paleozoic metasediments and granites of Gemericum unit and Cretaceous Rochovce granite, 10 – metabasic complexes in Rakovec and Klátov units, 11 – Cadomian basement in Zemplinicum unit, 12 – Cadomian basement below KB complexes).

However, a local decrease of gravity values was caused by the metasedimentary series of the Gelnica unit with bodies of the Permian Gemeric granites and Cretaceous Rochovce granite (anomaly No. 9). The northern edge of the Gemericum is built by the complexes of the Rakovec and Klatov units with predominant metabasics, which is reflected markedly in the local increase in gravity compared to the neighbouring units (anomaly No. 10).

In the eastern section of the Klippen Belt (KB), the local gravity high No. 12 is likely caused mainly by the uplift of the EP segment over the former subduction zone (e.g., Janik et al. 2011). The influence of Mesozoic complexes in this area is less important. This segment was the original bedrock of the KB sediments and drifted away from the EP in the later stages of development. It is also manifested as a non-conductive segment in the MT profiles (Vozár et al. 2022) and was also interpreted in the lithospheric models (Bezák et al. 1997a).

Horizontal gravity gradients

The third group of the CBA map features are the distinctive and sharp horizontal gravity gradients, which mainly reflect the linear tectonic structures (the faults). We would like to point out that, from geologically-known or assumed faults (which are marked in Fig. 1 and on the Tectonic map of the Slovak Republic), in this work, we interpret only faults which are visible in the CBA map.

The transpressional NE–SW, ENE–WSW and E–W strike-slip shear zones and brittle faults (Fig. 6) were the dominant controlling structures during the older Neo-Alpine tectonic phase propagation, often geo-physically contrasting the IWECA crustal segments of the EP embayment of the thin oceanic crust (the Magura Ocean, equivalent of the North Penninic ocean). They include the CCZ (following the border of the EP) and the Carpathian Shear Corridor (CSC) with several individual faults (main strike-slip corridor in the Northern part of Slovakia), more to the south is the Vepor deep-range fault zone, which is manifested on the surface as the Pohorelá shear zone (Phf) and represents the southern border of the main granitized block of the WECA against the block with prevailing metamorphic complexes. The Hurbanovo fault represents the southern border of the WECA blocks, while more to the south is Pelsonia and beyond that, other intra-Pannonian terranes. The Rába fault and Litava (Leitha fault) represent the southern borders of eastern Alpine units vs Pelsonia and WECA. The above-listed discontinuities represent important tectonic zones in the Neo-Alpine tectonic processes; they are block boundaries, which controlled the extrusion of the IWECA and other blocks towards the EP. The most prominent shear zone is the CSC, which involves several accompanying faults (Marko et al. 2017). Marginal faults of horsts in Western Slovakia likely originated in this stage, just like the Tatry, Ružbachy, Vikartovce and KB faults in Eastern Slovakia. Some NE–SW strike-slip faults visible in the CBA map are situated in the southern part of Central Slovakia as well, e.g., the Zdychava (Zd) faults, however, they are probably structures of older – Paleo-Alpine origin.

A distinctive ENE–WSW linear interface between the WCGL and higher-density crust emerges from the CBA map. It fits perfectly with the course of the well-known Vepor deep-range fault, which is masked in the west by young volcano-sedimentary cover. The Pohorelá shear zone is the surface expression of this structure, which, along with the Zdychava shear zone, are the southernmost prominent sinistral strike-slip dislocations in the frame of the southern part of the extruded IWECA block. But these tectonic discontinuities were likely found and operated as early as the Paleo-Alpine period of tectonic evolution.

The main N–S striking faults (Fig. 7) were activated in the subsequent trans-tensional and final extensional stage, which were linked to the eastward migration of the subduction zone and its retreat-steepening. This process triggered an extensional stage (the E–W extension) accommodated by significant N–S normal faults, such as the Štitnik (Št), Poľanovce (Pn), Zázrivá (Zz), and Hornád (Hn), as well as others faults. Many of the faults from the previous transpressional and transtensional stage inverted into normal faults, often delimiting the core mountains (e.g., Tatry Mts., Marko et al. 2022).

Also important in the structure of the Western Carpathians is the population of large E–W map-scale faults. The most prominent are located in the lower crust and represent the block boundary faults as the long-active Hurbanovo–Diósjenö fault (the Hurbanovo fault, sensu Fusán et al. 1971), which divided the IWECA and Pelsö units and were tectonically juxtaposed along this block boundary lateral ramp, eastward extruding the IWECA block. The E–W Rožňava (Ro) fault plays an equivalent role (Reichwalder 1971), representing a tectonic contact between the Gemericum and the Silicicum units. It is surficial expression of geophysical, well-detected, first-order deep-seated and old-founded crustal discontinuity.

Shallower, upper-crustal faults like the Tatry (Tt), Vikartovce (Vi) and Nízke Tatry (Nt) faults, which had originally developed as back-thrust faults (Marko et al. 2022), were reactivated in the extensional stage as normal faults after migration of the Carpathian active front to the east. In this stage, population of the E–W extensional (normal) faults was created as well. Collision in the front of the Eastern Carpathians was realized under conditions of strong E–W compression (Peresson & Decker 1997; Vass 1998). This stress field affects the WECA interior as well, since the far-field effect was appropriate for the creation of the E–W extensional (mostly normal) faults. These faults accommodated block tilting in the last stages of the Neo-Alpine evolution. The ESE–WNW linear anisothropy in the gravity field, which crosses the Považský Inovec Mts. crystalline core and the South Veporic unit, was discovered by Pašteka et al. (2017) and shown in the reprocessed Bouguer anomaly map where it was likely a fault structure created and activated during this period. This linear structure seems to be a slightly sinistrally offset western directional continuation of the Rožňava fault. The Rožňava fault has the same course and its western continuation, which is

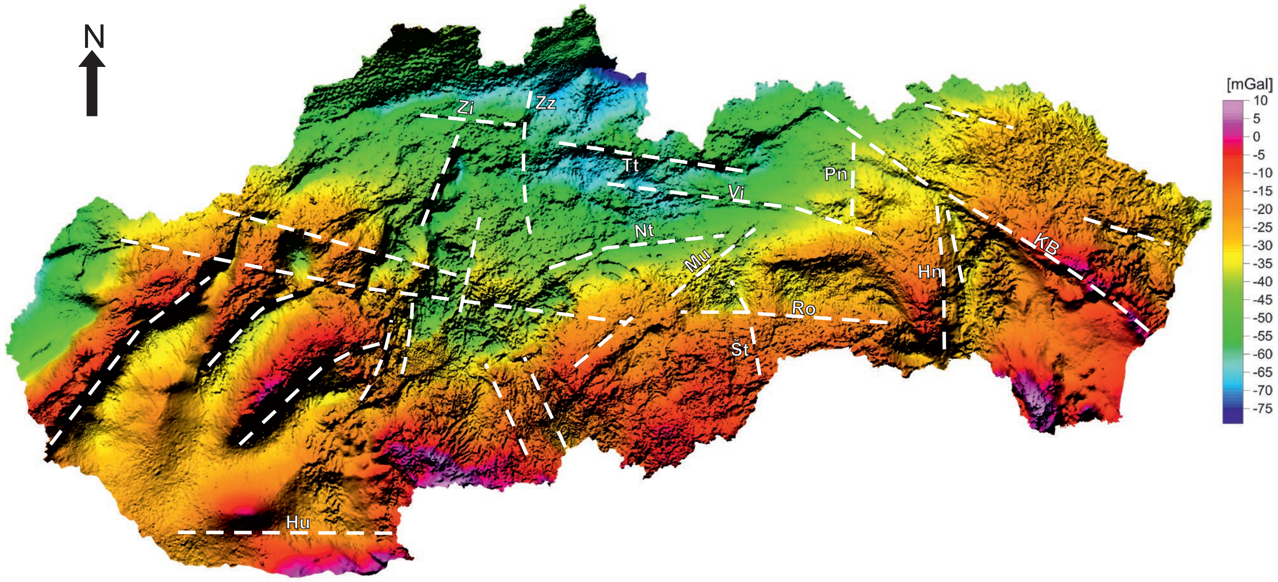

Fig. 7. The most important faults active during Neo-Alpine transtensional and extensional stages (Hu = Hurbanovo, Zi = Žilina, Zz = Zázrivá, Tt = Tatry, Vi = Vikartovce, Ru = Ružbachy, Nt = Nízke Tatry, Mu = Muráň, Pn = Poľanovce, Št = Štítnik, Ro = Rožňava, Hn = Hornád, KB = Klippen Belt, names of others see Fig. 6 or they are unnamed).

shifted sinistrally by the Štítnik (Št) fault (Varga 1971; Snopko 1971), fits perfectly with the line interpreted from the CBA map (Fig. 7). However, this line, in contrast with the Rožňava fault, does not represent a significant deep-rooted geophysical boundary; it could represent a shallow-crust structure, because it is indicated by steep gravity gradients (Zahorec et al. 2017b).

During the latest stages of the Carpathian loop formation, a steepening of subduction of the ocean crust in the Eastern Carpathians occurred due to the roll-back effect (Royden et al. 1982), which strongly pulled the Carpathian units towards the East. The far-field effect of this process in the Western Carpathians was the activization of the E–W dextral and the ENE–WSW sinistral strike-slips with a moderate magnitude of motion, including a component of normal separation due to the trans-tensional regime operated along these faults. The marginal faults accommodated the final emplacement of the Inner Western Carpathian segments. The NW–SE dextral strike-slips could have played a similar role, also with a component of normal separation, which are so numerous in the Western Carpathian architecture. Due to the far-field effect of the distal slab-pull, a third population of numerous extensional N–S faults was generated or reactivated as well. These faults accommodated a moderate final shift of crustal segments towards the east, and they are quite evident in the recent structure of the Western Carpathians.

Neotectonic activity of the E–W faults is expected. Along the Vikartovce (Vi) fault, a approximately 130 m dip-slip separation has been confirmed, which took place approximately 130 Ka ago (Vojtko et al. 2011). Similarly, more extensive Neotectonic motion should have occurred along the Tatry fault, however, the fault trace is covered by huge fluvio-glacial depositions on the surface, which unfortunately complicates direct field research.

Recent activity of some the E–W and N–S faults is declared by observed micro, even macro-seismic events generated at the Žilina segment of the KB and Hurbanovo–Diósjenö fault zone (Fusán et al. 1979; Kvitkovič & Plančár 1979; Procházková et al. 1986; Čech 1988; Cipciar et al. 2016).

Discussion

The WCGL is the most striking phenomenon in the CBA map. It has been interpreted several times in the past (e.g., Tomek et al. 1979; Pospíšil & Filo 1980; Ibrmajer & Suk 1989). Most recently, the WCGL was divided into two gravity sub-lows: the Outer Western Carpathian gravity low and the Inner Western Carpathian gravity low, since their sources are completely different (Bielik et al. 2022). The source of the Outer Western Carpathian gravity low is the low-density sediments of the OWECA and the Western Carpathian Foredeep. However, the source of the Inner Western Carpathian gravity low is a result of the gravity effects of complexes of granitoid character in the Tatricum and partly within the Northern Veporicum (Ľubietová zone), which has an analogous lithological composition like the Ďumbier zone of the Tatricum. For this gravity effect, the thicker crust also contributes (up to 42 km, Bielik et al. 2018) in the NE of the Tatra Mts., which was partly explained as a kind of remnant of the small crustal root formed during the collision of the European Platform with the IWECA block (Lillie et al. 1994). Indeed, the Inner Western Carpathian gravity low is mainly caused by the Tatricum granitoids and orthogneisses, which is documented by geological and geophysical data. Moreover, we would expect such a crustal root remnant mainly where subduction is most evident, i.e., in the eastern segment of the Western Carpathians. But here, we suppose that a negative gravity effect of this crustal remnant is significantly weakened by the action of the asthenolith, which brought it closer to the surface and increased not only the heat flow, but also the gravity values. The presence of the asthenolith uplift caused the WCGL to stop continuing towards the SW, even though the Tatricum and Northern Veporicum complexes of a granitic character from the Central Slovakia segment also occur in the crust in this area. Thus, before the beginning of the asthenolith influence, the WCGL represented a complete SW–NE oriented tectonic block (terrane), which was in contact with the European Platform along the CCZ in the north, and it contacted a tectonic block with dominant metamorphites along the Phf in the south. The Phf, originally defined as a fault between North and South Veporicum units, appears to be an important shear zone of an older age (Upper Paleozoic and then Cretaceous activity is assumed, Bezák 2002), however, we assume activity also during the Cenozoic, mainly in the deeper level of the crust below young sedimentary and volcanic complexes.

Similarly, but even more intensively, the asthenolith and crustal thinning also acted in the eastern segment, where it even reached below the flysch zone. However, the source of asthenolithic masses following the thinning of the crust in the west and east was not identical. In the west, it was connected to the processes in the Pannonian Basin and penetrated from the SW, which can also be seen in the heat flow map of the entire area (Majcin 1993). In the east, it penetrated from the SE from the advancing subduction zone, and the volcanics of the eastern segment were related to it. As subvolcanic intrusions, these igneous rocks were also identified in the flysch belt (e.g., Kucharič et al. 2013; Majcin et al. 2014). The new MT models in Eastern Slovakia also show the likely progress of asthenolithic masses from the SE (Vozár et al. 2022*)*.

The gradual migration of tectonic blocks from the SW around the Alps into the area of the Outer flysch basin is an important phenomenon for the tectonics of the WECA. This phenomenon has been known for several decades (see the citations in the chapter Geological setting). The filling of the flysch basin by these tectonic blocks took place in a transpressional regime along the shear zones. In the case of the WECA, the most important are CCZ, CSC, Phf, Hurbanovo, Diosjenö. The WECA block and Pelsonia block, separated from the EA by the Rába fault and from the WECA by the Hurbanovo fault, were the northernmost blocks of the crust that were extruded from behind the Alps into the Magura zone. The shear zone in the center of the WECA, which was described by geophysicists as a deep Vepor fault that projects into the Phf on the surface, is a very interesting phenomenon. The beginnings of this shear zone can be traced back to the Permian (Bezák 2002), where it could have been a significant discontinuity in the formation of the Fatricum nappes in the Paleoalpine period. However, it certainly played a role later in the approximation of the basements with a diametrically different Mesozoic cover (Northern and Southern Veporic units). In the current tectonic setting, Phf separates two blocks with different physical (density, electric conductivity) properties and also separates two blocks with a different nature of interaction with the EP (oblique vs direct collision, Bezák et al. 2021). It is difficult to assess to what extent this long predisposed zone functioned in the Neoalpine period. Its manifestation is hidden in the depths (under the Cenozoic sediments and volcanics) rather than in the surface structures.

Conclusion

The new CBA map of Slovakia (Pašteka et al. 2017) provides very important data for the interpretation of the geological structure, composition, and tectonics of the Western Carpathians. There are very good correlations of the gravity features in the CBA map with the known geological structures described in the geological maps of Slovakia (e.g., Bezák et al. 2008). These correlations are as follows:

- The territory of Slovakia can be divided into three basic segments in terms of gravity characteristics and their sources (Fig. 2). In Central Slovakia, the low-density segment (the WCGL, segment A) consists of two gravity sub-lows: the OWCGL (field A1) and the IWCGL (field A2). The source of the OWCGL is the low-density Outer Western Carpathian flysch sediments and partly the Neogene sediments of the Carpathian foredeep. The IWCGL is caused by the complexes of a granitic character, whose average density is lower than the average crustal density in this area. South of the IWCGL is the segment B, which is composed mainly of higher density metamorphic complexes and is also characterized by a thinner crust. The segments marked C (C1 in Western and C2 in Eastern Slovakia) show a strong influence of the asthenolithic masses and crustal thinning.
- Several local anomalies also occur in all segments, but mostly in the area characterized by positive gravity values. They can be explained by the well-known geological structures and morphology of these areas. Local gravity highs are created by the core mountains in Western Slovakia (e.g., the Malé Karpaty Mts., the Považský Inovec Mts., the Tríbeč Mts.). The largest local gravity high is represented by the subvolcanic basic body in the Kolárovo area. Furthermore, it is the Cadomian basement in the lower parts of the Pelsö unit south of the Hurbanovo fault, further in the lower parts of the Veporicum complexes mainly south of the Rapovce fault (xenoliths, borehole, magnetic data), and in the lower part of the crust south of the Rožňava fault and in the Zemplinicum. Significant local positive gravity anomaly is caused by the basic complexes of the Klátov and Rakovec units in the northern Gemericum. In the eastern section of the KB, the local positive gravity anomaly is due to the higher average density, which most likely represents the drifted EP block (the so-called Pieninic crust). The areas with relatively lower average densities are mainly occupied

by thick sedimentary Cenozoic complexes (e.g., the Liptovská kotlina Basin, the Levočské vrchy Mts., the Oravská Magura Mts.), thick metasedimentary Paleozoic series (the Gelnica unit) with Permian granitoids, and Cretaceous Rochovce granite.

- The linear tectonic structures are of tectonic origin and represent either a steep gravity horizontal gradient between density contrasting blocks (e.g., at the contact zone of the core mountain ranges and the basins) or they are distinct fault structures. They were mostly formed in the youngest stages of the tectonic development of the Western Carpathians in the Neogene (Neo-Alpine stage), but they can also be older among them. The Neo-Alpine stage had its own sequence, when tectonic structures were first formed in the transpressional stage of development (mainly from the NE and less by the E–W direction faults). Later, structures were operated in the transtensional stage (mainly in the E–W and the NW–SE directions) and simultaneously generated important N–S faults (e.g. the Št, Pn, Hn faults). In the final extensional stage, many fault structures from the previous stages were reactivated, but the basic tendency of the movements was not horizontal but vertical.

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