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Contrasting tectonic styles of the western and eastern parts of the Western Carpathian Klippen Belt in Slovakia based on magnetotelluric sounding of deep tectonic structures

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To characterize the deep structure of the Klippen Belt, we made magnetotelluric measurements in profiles across the western and eastern segments in the territory of Slovakia, from which we created 3D models. The models revealed significant differences in tectonic structure between these segments. In the western segment, the Klippen Belt is located in the southern reversing wing of the original subduction flower structure (retroarc thrusting) with an overthrust to the south onto the Inner Western Carpathian units. This structure was later modified by significant transpressional movements. In the eastern segment, the Klippen Belt is primarily an organic part of the accretionary wedge of the Outer Western Carpathians and it is overthrusted onto the Flysch Belt. This was followed by modification of the structures, mostly in a transpressional regime, including local reversing overthrusts and the development of a steep fault boundary, mainly along the southern margin, against the Inner Carpathian Paleogene succession. These differences between the structure of the western and eastern Klippen Belt segments indicate the contrast between the interaction of the western and eastern parts of the Inner Western Carpathians with the European Platform. In the western part, oblique collision and sinistral transpression dominate. In the eastern part, by contrast, subduction and orthogonal collision dominated over later transpressional modifications.

Key words: Western Carpathians, Klippen Belt, magnetotelluric sounding, deep structures, subduction, collision, transpression.

INTRODUCTION

The tectonic style of the interaction of the Inner Western Carpathian (IWC) Block with the European Platform (EP) has been described in many studies concerning the development of the entire Alpine-Carpathian-Pannonian region during the Miocene. Research into the development of the Klippen Belt (KB) can play an important role in understanding this region. We use the more general term “Klippen Belt” following the terminology of the Tectonic Map of Slovakia (Bezák et al., 2004), and with regard to its various named sections (e.g., Kysuca, Orava, Pieniny, Šariš segments). This seems appropriate, although in the literature the term Pieniny Klippen Belt is more commonly used. The KB lies on the border of the Outer Western Carpathians (OWC) and IWC and thus its deeper structure may reflect the character of IWC/OWC contact.

The lateral extrusion process of the Carpathian-Pannonian terranes from the area of the Eastern Alps under pressure from the Adria microcontinent into the area of the North Penninic flysch basin has been described in several studies (e.g., Ratschbacher et al., 1991; Beidinger and Decker, 2016). Other studies have looked into the Neogene evolution of the Carpathian-Pannonian region where subduction of oceanic crust covered by flysch deposits was followed by collision and the formation of Neogene basins associated with volcanic activity (Royden et al., 1982; Csontos et al., 1992; Nemčok et al., 1998; Lexa and Konečný, 1998; Fodor et al., 1999). Most of the studies have concluded that, in the case of the Western Carpathians, oblique collision of the IWC Block with the EP occurred, accompanied by sinistral transpression (e.g., Sperner et al., 2002).

The position of KB at the border of the IWC and OWC has always been subject to debate. KB complexes, as remnants of the Mesoalpine orogen, became part of the IWC Block together with Palaeoalpine units, and were located in the IWC foreland. At the Neoalpine stage of tectonic evolution, they participated in the development of an accretionary OWC wedge, and later they became part of the transpressional zone. The transpressional movements led to refolding of the KB units, the creation of flower structures, and backthrusting associated with strike-slip move-

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ments (e.g., Ratschbacher et al., 1993; Jurewicz, 1997; Pešková et al., 2009; Ludwiniak, 2018) and/or earlier subduction (e.g., Birkenmajer, 1986). Therefore, during the geological mapping of the KB zone, all structures (the north-vergent overthrust, transpressional, and backthrusts) were identified. All these structures were a consequence of a complicated tectonic development, and each structure reflected one of its stages.

The KB zone is relatively very well explored. The reconstructions of the tectonic development of the KB were based mostly on surface mapping (the region we studied is covered mainly by the geological maps of Haško and Polák, 1978; Nemčok, 1990; Gross et al., 1994; Janočko et al., 2000; and Teťák et al., 2016) with supporting structural and stratigraphical records and rare boreholes. Based on these works, further concepts of the tectonic development of the KB in its separate sections were published (e.g., Kováč and Hók, 1996; Krobicki et al., 2003; Oszczypko and Oszczypko-Clowes, 2014; Jurewicz, 2018). The structural measurements indicated also differences between the tectonic development of the western and eastern segments (Plašienka et al., 2019). Our goal was to use geophysical methods to examine KB's position at deeper levels (3–5 km), comparing KB structures at this deeper level with existing concepts of its development. MT emerged as the most suitable method for this study since the resolution of gravimetry is less sensitive to lithology and seismic analysis is less sensitive to steep structures and to lithological variation. MT, by contrast, was sensitive to the lithological properties of the rock bodies we studied. Therefore, we implemented MT sounding in three profiles across the KB in its western and eastern segments (Figs. 1 and 2) to examine the deeper structures along the contact zone between the IWC Block and EP. We also used the newly modelled MT-4 section in the eastern part of KB (Majcin et al., 2018). The area that lies between our profiles, summarized in the work of Golonka et al. (2005), is a rich source of information, especially regarding boreholes and MT profiles. For comparison, we also used seismic, gravimetric and magnetic data (Vozár and Šantavý, 1999; Janik et al., 2009; Hrubcová et al., 2010; Bielik et al., 2010; Grabowska et al., 2011; Kucharič et al., 2013) and mainly MT models from western Slovakia (Kováčiková et al., 2005; Bezák et al., 2014), eastern Slovakia (Ryłko and Tomaś, 2005) and Ukraine (Kováčiková et al., 2019).

This work is a contribution to the long-term research of KB, a geological phenomenon which since the 19th century has engaged generations of excellent geologists. We obtained a closer view of the deeper structures of KB and neighbouring units based on the MT survey, and use the new geoelectrical MT image to discuss the structural development processes and their causes .

GEOLOGICAL SETTING

The geology of the Western Carpathians (WCp) is well-documented in recent synthetic maps (e.g., Lexa et al., 2000;

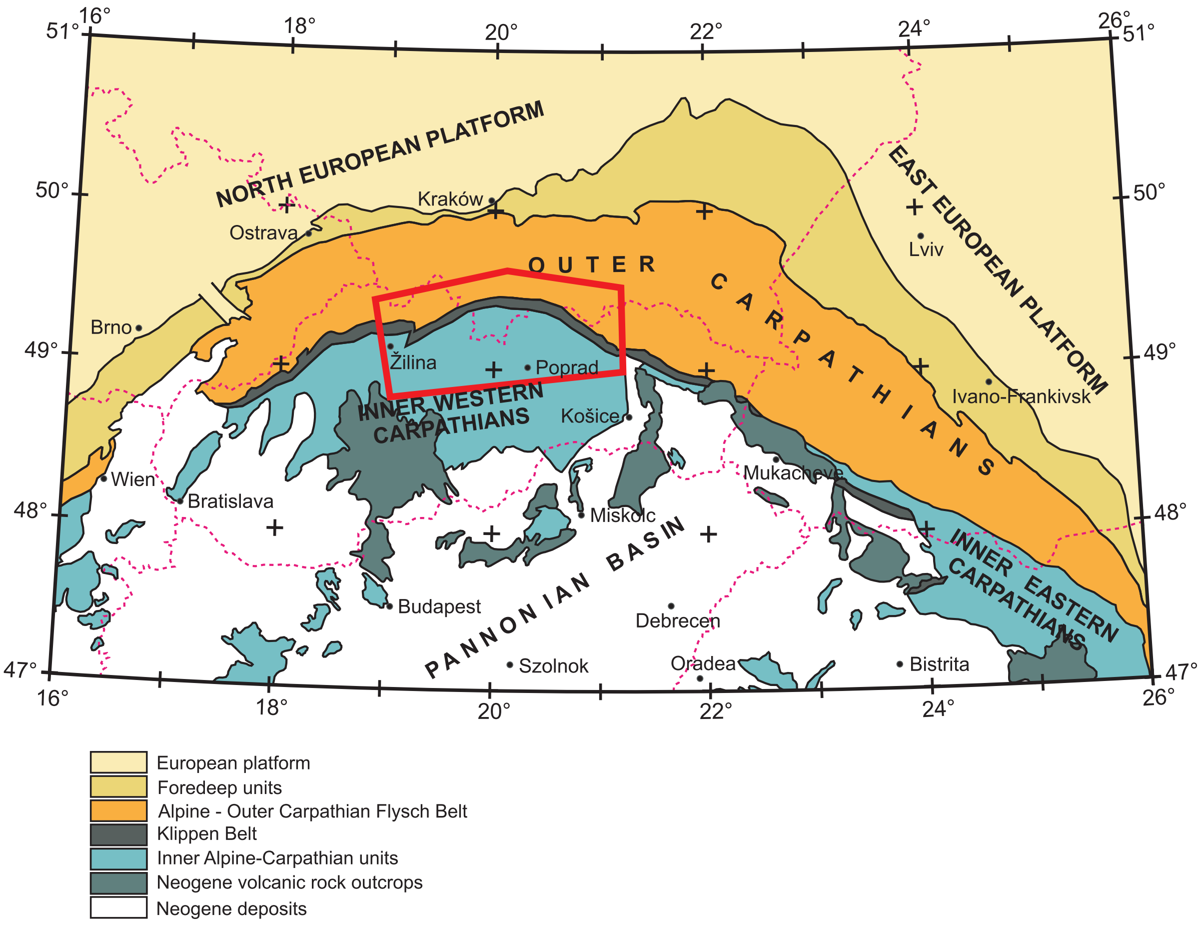

Fig. 1. Location of the area studied (red polygon) in the northern part of the Carpathian-Pannonian region, with generalized tectonic map modified after Majcin et al. (2018)

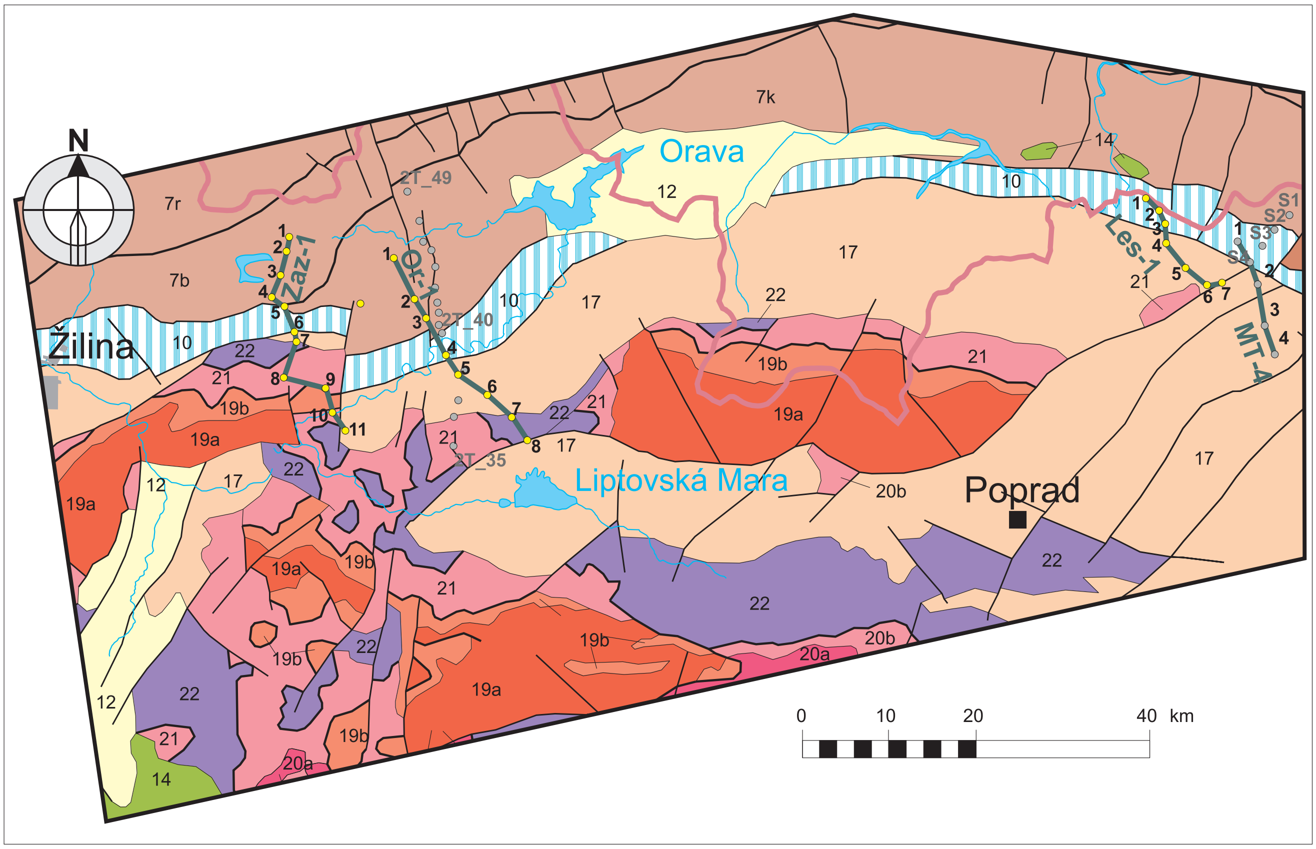

Fig. 2. Position of measured new MT sites (yellow circles) on the profiles Zaz-1, Or-1, Les-1, remodeled MT-4, and older sites used in modelling along the profiles 2T and S-1 in previous studies (grey circles)

Geological context after Lexa et al. (2000): 7 – Magura Unit of the Flysch Belt: r – Rača, b – Bystrica, k – Krynica Nappe, 10 – Klippen Belt, 12 – Neogene deposits, 14 – Neogene volcanic rocks, 17 – Inner Western Carpathian Paleogene units, 19 – Tatricum Unit: a – crystalline basement, b – Mesozoic sedimentary cover, 20 – Veporicum Unit: a – crystalline complexes, b – Mesozoic sedimentary cover, 21 – Fatricum, 22 – Hronicum

Bezák, 2008) and in many other publications. It has been recently summarized in the studies of Biely (1989), Plašienka et al. (1997), Froitzheim et al. (2008), Bezák et al. (2011) and Plašienka (2018). In this study, we focus mainly on those elements of geology which have a direct relation to the issue addressed by this manuscript.

Recent maps (e.g., Lexa et al., 2000) document the morphology of WCp as an arc mountain range, the nature of which is delimited by the OWC Flysch Belt (FB). It is an accretionary prism comprising flysch strata pushed up from the ocean basin on the southern border of EP by the pressure of the advancing IWC blocks, which gradually filled this basin area, with eventual collision that gave the whole mountain range its final shape.

The IWC Block (upper plate in the collision) is formed by the Palaeoalpine (Cretaceous) crustal and superficial nappes and post-nappe Cenozoic sedimentary and volcanic formations. The crustal nappes are formed of the Hercynian crystalline basement and its Upper Paleozoic and Mesozoic cover, and the superficial nappes only of Upper Paleozoic and Mesozoic sequences (e.g., Plašienka et al., 1997). The crystalline basement contains several Hercynian tectonic units composed of metamorphic complexes and granitoids (Bezák et al., 1997). During the succeeding Mesoalpine collision, the IWC units also absorbed the KB units (sedimentary deposits and their crystalline basement), these being the result of closure of the South Penninic Oceanic Basin in the former IWC foreland.

The IWC Block formed in these previous processes, together with other (Pannonian) terranes (Pelsonia, Tisia, Dacia), was pushed into the North Penninic oceanic area during the Neoalpine subduction of this basin, and gradually collided with the EP.

The following basic tectonic units are parts of the geological structures in the area studied (Fig. 2): from the north, there is the FB as an accretion prism OWC thrusted onto the EP, the KB zone at the front of IWC units and then other Palaeoalpine units of Tatricum, Fatricum and Hronicum in the Malá Fatra Mts., Chočské vrchy Mts., Tatry Mts. and the “Ružbašský ostrov”. Transgressive ICP deposits lie on these Palaeoalpine-formed units. Today they are preserved within grabens, separated by Neoalpine faults from the mountains. The most significant faults in this area include the Prosiek, Tatry, Vikartovce, Ružbachy and Branisko faults, and faults lining the KB. ICP units also appear separately in mountains such as the Levočské vrchy Mts. and Spišská Magura Mts., as remains of an extensive fore-arc basin.

Different opinions have been expressed as regards the tectonic evolution of the KB. The studies of Andrusov (1974), Krobicki et al. (2003), Golonka et al. (2019), and others summarized the development of the KB as representing two main orogenetic phases: a Laramian Late-Cretaceous (Mesoalpine) phase, which gave rise to the system of north-vergent nappes after subduction of the South Penninic ocean between the IWC and Middle Penninic continental ribbon (Oravic basement); and a post-Paleogene (Neoalpine) phase, when the original morphology was segmented into today’s isolated blocks. Early stages of the evolution of the KB were studied, e.g., by Nemčok and Nemčok (1994), Oszczypko (2006), and Plašienka (2012).

The sedimentological studies of Mišík et al. (1981), Marschalko (1986), Oszczypko et al. (2005), and others were an important tool for the palaeotectonic reconstructions. Some studies described a large proportion of olistoliths in the composition of the KB (Nemčok, 1980; Golonka et al., 2015). Nevertheless, tectonic studies dominate as regards the KB, especially those concerning subduction and transpression processes (e.g., Birkenmajer, 1986; Ratschbacher et al., 1993; Oszczypko et al., 2010; Jurewicz, 2018; Ludwiniak, 2018).

One of the most discussed questions concerns which exactly units belong to the KB. In the General Geological Map of Slovakia at 1:200,000 (Bezák, 2008), this issue was resolved by conventionally defining the KB *sensu lato* as a transpressional Neogene tectonic structure. In the formation of this structure, in addition to the KB *sensu stricto*, neighbouring units of the IWC and FB also took part. The previous development of the KB *sensu stricto* units can only be speculated on indirectly, using the the lithology of the successions and analogies with other Southpenninic units, especially in the Eastern Alps. While in the Alps units of the Mesoalpine orogeny are covered by massive Austroalpine nappes and come to the surface only in tectonic windows (Rechnitz, Tauern), the structure of the IWC only contains fragments of them in the foreland of the transported IWC Block. In the deeper structure, we also infer the presence of continental ribbons (relics of Middle Penninic-type crust), which have been referred to as Oravic basement or as Pieninic crust (e.g., Grad et al., 2006). These geological labels are used in our profiles.

Those seismic sections that have penetrated the KB (e.g., Tomek and Hall, 1993; Janik et al., 2009; Hrubcová et al., 2010) indicate its relatively shallow depth, although interpretation is difficult because of the steep inclination of the structures. In each case, the KB does not resemble an important suture zone, which has to be found at the border of EP and IWC. We suppose that this border is indicated by the Carpathian Conductivity Anomaly Zone (CCA), which is the most significant linear conductive crustal structure along the Carpathian Arc at a depth of 10–20 km (Jankowski et al., 1977; Buryanov et al., 1987). The CCA has been investigated by the magnetovariational method (Červ et al., 2001; Kováčiková et al., 2005), which detects only magnetic components in sounding, and the magnetotelluric (MT) method, which combines magnetic and electric fields, in deep profiles crossing the Vysoké Tatry Mts. (Ernst et al., 1997) and eastern Slovakia (Ádám et al., 1997). The most accepted hypothesis for the higher conductivity involves petrology, *via* the presence of mineralized water or of graphite (Vanyan, 1997; Hvoždara and Vozár, 2004; Jankowski et al., 2008; Majcin et al., 2014).

METHODS

In our study, we used the MT method, which utilizes naturally occurring temporal variations in the electromagnetic field to image the subsurface distribution of electrical conductivity (Tikhonov, 1950; Cagniard, 1953). We focused on MT measurements along two NW–SE oriented profiles cross-cutting the KB in the Zázrivá area (western segment). The sections were situated to the west (Zaz-1 profile) and east (Or-1 profile) of the Zázrivá Fault Zone, as different tectonic styles are inferred on both sides of this perpendicular transform fault. In the eastern segment of KB, we measured one NW–SE oriented profile in the Lesnica area in the Pieniny region (Les-1 profile). The location of profiles measured is shown in Figure 2. We remodeled also older data along the MT-4 profile parallel to Les-1 (Fig. 2).

The geological situation of all profiles measured is similar. The two western profiles start in the FB, cross the KB and the Inner Carpathian Paleogene (ICP), and end in Fatricum and Tatricum (Zaz-1), or Hronicum (Or-1*)*; the eastern profile starts in the northern part of the KB and continues to the ICP. The interpretation of MT measurements (the models in Figs. 3 and 4) was aided by the conductivity contrast between the lithological contents of participating tectonic units (in general, the least conductive structures are the crystalline rocks of the IWC and PC, more conductive are the Mesozoic rocks of the IWC and KB, and the most conductive are the Paleogene deposits of the FB and ICP and the fault and aquifer zones).

In total, 26 points have been measured by broadband MT instruments (*Metronix GmbH GMS-07e*) with induction coil magnetic sensors. The MT data collected were processed to impedance transfer functions and modelled by MT inversion codes to estimate the best-fitting 3D conductivity model. The processing of MT data was performed by a Metronix Mapros processing package (Friedrichs, 2003) with implementation of the robust method. Different rejection techniques were used to estimate the impedance transfer function in the 0.0001 to 100 seconds range. The data quality near the Zázrivá Fault of the sounding curves decreased to the south due to the presence of a DC traction railway and most of the periods >1 second were distorted, these periods not being used in the final models. In Appendix 1* we show typical sounding curves for sites located in the OWC and IWC. For the western sites, more conductive shallow structures and higher apparent resistivities for longer periods are typical. The stations closest to DC railway are heavily distorted at longer periods. The eastern MT sounding curves show the more resistive shallow structures of the IWC.

As stated above, the modelling was divided into two separate modelling areas with 19 new sites in the west with additional information from the old 2T MT profile (15 sites) and the 7 new sites in the east, where 9 older sites were added for modelling. The full impedance tensor data were inverted by 3D ModEM inversion code (Egbert and Kelbert, 2012; Kelbert et al., 2014), which allows parallel calculation of the inversion of impedance on the High Performance Computing cluster. We decided to use 3D inversion of MT data distributed along the profile to avoid problems with 3D effects and its artefacts in 2D decomposed data, which can lead to unreal structures within the 2D inversion model. Using 3D modelling instead of 2D is a common practice in the geoelectrical community (Meqbel et al., 2016; Kirkby and Duan, 2019). Particularly for the Zázrivá area, 3D modelling is necessary due to the offset of the KB, which can lead to missing well-known regional crustal structures as shown by Vozár et al. (2021) by comparison to older 2D and newly developed 3D models. Also, in the east there are expected to be perpendicular structures with a strong change in geoelectrical strike angle. The dimensional analysis of inverted new MT data

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* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1595

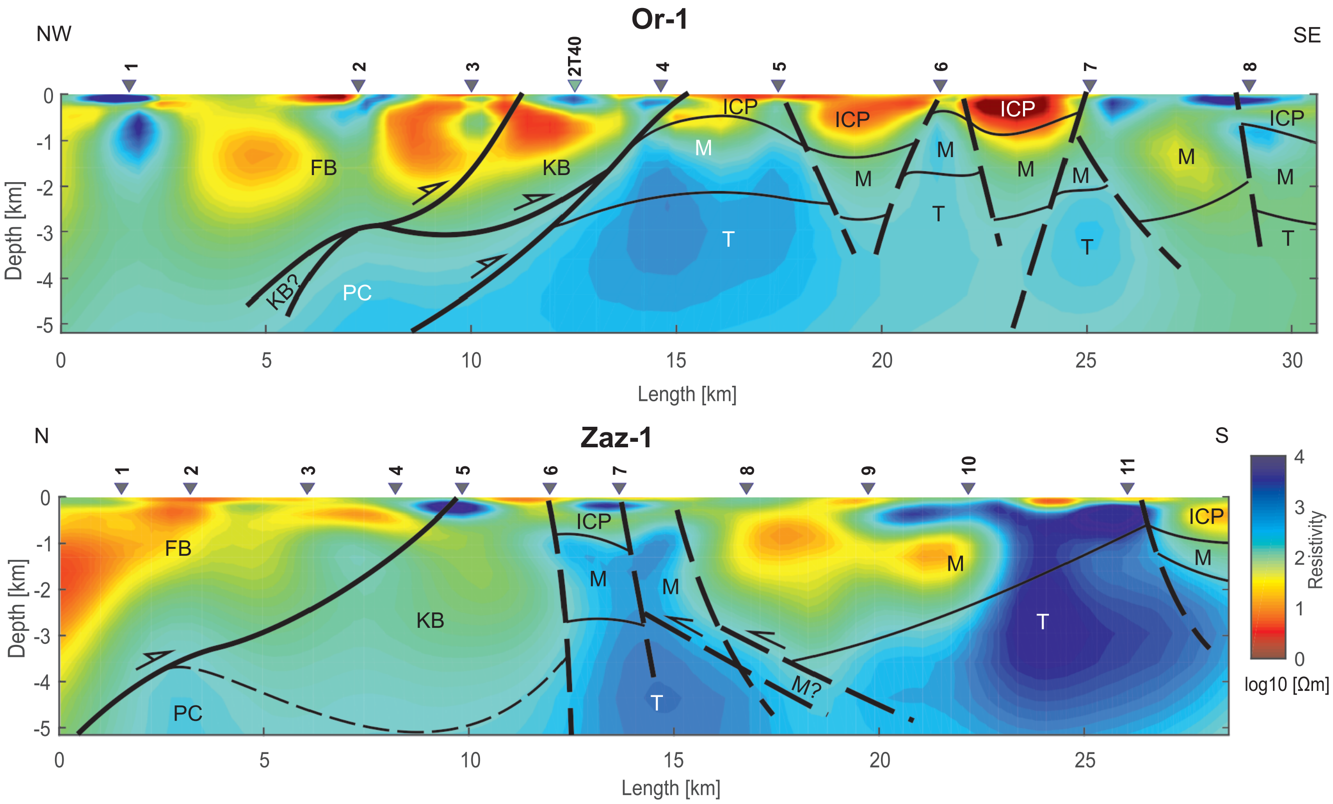

Fig. 3. Geological interpretation of the sections Or-1 (upper part) and Zaz-1 (lower part) from the western 3D geolectrical model

FB – Flysch Belt, KB – Klippen Belt, PC – Pieninic crust, ICP – Inner Western Carpathian Paleogene deposits, M – Mesozoic units undivided (cover units and nappes), T – Tatricum crystalline basement; open arrowhead – back-thrusting, simple arrowhead – younger shortening, dashed lines – faults (normal and strike-slip)

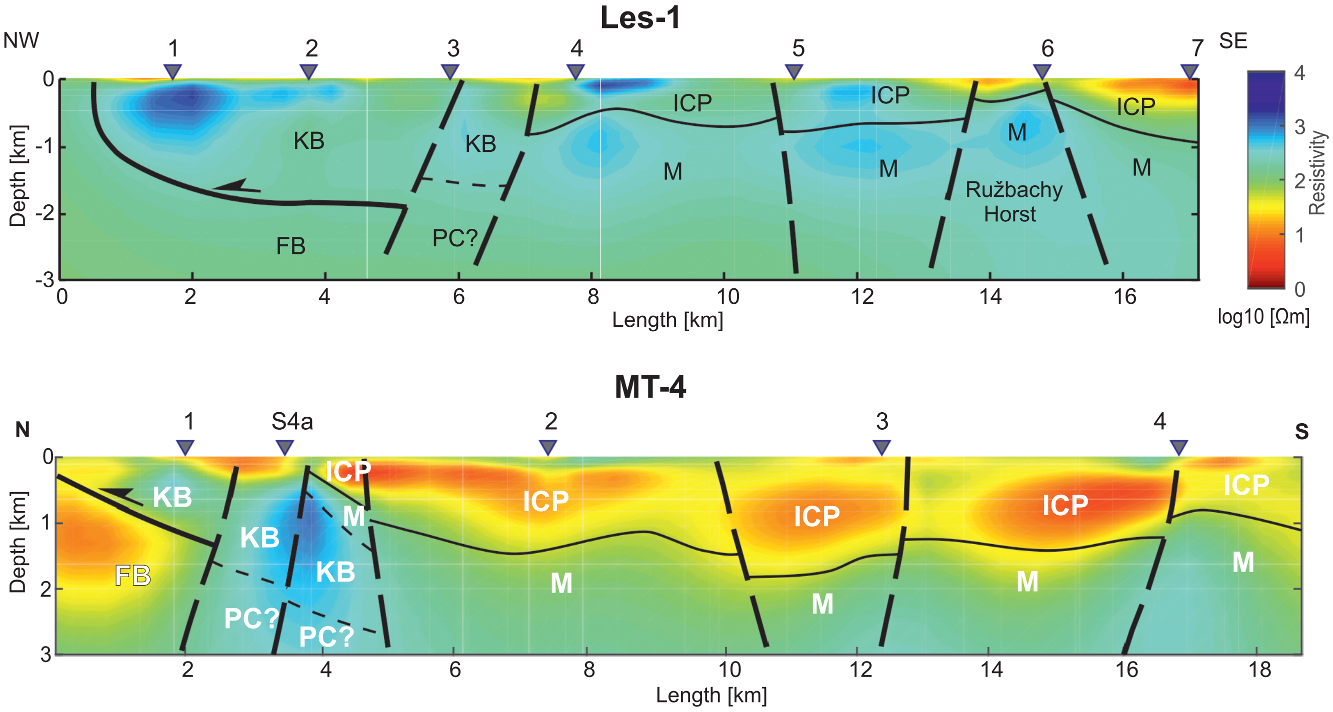

Fig. 4. Geological interpretation of the sections Les-1 (upper part) and MT-4 (lower part) from the eastern 3D geolectrical model

Filled arrowhead – thrusting, open arrowhead – backthrusting; dashed lines – faults (normal and strike-slip); for other explanations see Figure 3 based on phase tensors (Caldwell et al., 2004) are included in the supplementary part (Appendix 2), where a magnitude skew angle over 3 indicates 3D subsurface structures.

After preliminary testing of starting inversion and regularization parameters, a starting half-space model with 100 Ωm resistivity was used in the final best-fitting inversion model. The final normalized RMS for the Zázrivá model was 2.55 and 2.24 for the Lesnica area (Appendices 3 and 4).

RESULTS

In the Or-1 section (upper part of Fig. 3), flysch strata show the highest conductivity in the outer FB as well as in the ICP. KB complexes have a lower conductivity, in particular for the Zaz-1 section (lower part of Fig. 3). Crystalline rocks in the Pieninic crust (PC) following Grad et al. (2006) i.e. Pieninic (or Oravic) basement, as well as in the Tatricum Unit, are very resistive. The rocks of the Mesozoic are also very resistive unless conductive water and crushed zones are present. Contamination by conductive fluids and fractured zones are visible between points 7 and 8 in profile Or-1 (in the area of the Chočské vrchy Mts.) as well as on the northern slopes of the Malá Fatra Mts. between sites 8 to 10 in the Zaz-1 section. In cross-sections Les-1 and MT-4 (Fig. 4) there are contrasting resistive KB complexes with underlying conductive FB sequences. The only conductive levels are in ICP successions and also in a small part of the KB (probably comprising shale and sandstone). It is possible to distinguish two sub-units according to Jurewicz (1997) – an upper Pieninic Nappe with variable lithology and a lower more homogeneous part of a subpieninic nappe. Quaternary water-saturated units probably exist at shallow depths near sites 6 (Les-1) and 1 (MT-4). We infer the existence of a narrow protruding part of the KB with PC crust in their basement (Fig. 4).

Both sections through the 3D MT model of the western segment (Zaz-1, Or-1; Fig. 3) share the same mean feature – the movement of FB successions to the south through KB complexes and their bedrock (PC). In the Or-1 profile, we can identify the overthrust of KB complexes together with the PC onto the IWC units (ICP, Mesozoic successions, and Tatricum crystalline rocks). This is in direct contrast to the models in the eastern part (Fig. 4) where KB complexes are torn off from their bedrock and overthrusted onto the FB successions.

The back overthrust of the southern part of the FB in the western section was formerly mostly interpreted as connected with strike-slip movement (e.g., Kováč and Hók, 1996; Pešková et al., 2009; Teťák et al., 2016). According to the results from some seismic sections and the 3D MT model on the 2T seismic section (Vozár et al., 2021), the position of the KB could be primarily the result of initial subduction-collisional processes. The KB in this process, with the southernmost part of the FB and the northernmost units of the IWC, formed a reverse (in this case southern) wing of the flower structure (retroarc thrusting). It follows that the subduction zone was located N of the KB, approximately in the area of the CCA manifestations, as we earlier inferred (Kucharič et al., 2013).

This type of flower structure, created during subduction and oblique collision, is generally described in Dadlez and Jaroszewski (1994), Press et al. (2004), Yeats (2012), and others. For our region it was proposed by Birkenmajer (1986). All other tectonic processes then modified the original structure to varying degrees. These mainly included the transpressional movements, but the Zaz-1 section also shows the effect of younger compression and the emergence of a steep fault boundary of the KB in the south against the IWC units (lower part of Fig. 3). The transverse Zázrivá Fault runs between our sections Zaz-1 and Or-1. The changes on both sides of this fault were initiated possibly also by the morphology of the EP. We tried to identify this fault by 3 extra broadband MT sites situated along the east-west line, and also by a short control source MT profile which crossed this fault structure. Unfortunately, the data from all broadband MT sites were heavily distorted and could not be used in modelling. The control source profile is very shallow and was not able to identify deeper structures associated with the fault.

By contrast, we clearly see the original position of the KB in the eastern section (Les-1 and MT-4 slices of 3D eastern models, Fig. 4) as part of the accretionary prism in the overburden of the flysch nappes. Previous workers also arrived at the same results based on detailed structural research (Jurewicz, 1997, 2018; Oszczypko et al., 2010; Plašienka et al., 2012). This position is only slightly modified in some places by later backthrusts (Plašienka et al., 2013). The accretionary prism is mostly bounded to the south (on the boundary with the ICP) by a steep fault (Podhale Fault) described in several previous studies (e.g., Jurewicz, 1997; Ludwiniak, 2018), which has also been identified in older MT profiles (Majcin et al., 2018). A fault boundary is present also on the northern side of the KB or sometimes within the KB. This is apparently the consequence of transpressional tectonics. In this way, all of the wide KB zone should be segmented into more parts (e.g., Šariš transitional zone in the sense of Jurewicz, 2018, the zone with only KB with its PC basement, and an internal zone where the original position of the KB with PC under IWC complexes is supposed to be (e.g., MT-4 profile or older MT-15 profile; Bezák et al., 2014).

DISCUSSION

The tectonic development of the KB is seen as an indicator of the character of tectonic processes between the IWC Block and EP due to its position on the boundary of the OWC and IWC. There is an obvious difference between the types of tectonic regime in the western and eastern segments. An accretionary wedge of a flower shape was formed in its western section in the first stages of subduction and oblique collision. It is identified in the deep MT 3D model along the 2T seismic profile (Vozár et al., 2021). The southernmost parts of the FB and KB units are located in the reversed wing of this flower structure, which is shifted to the south together with part of the frontal Inner-Carpathian units. This type of collision rapidly changed in this segment into a transpressional regime. The contact between the EP and the IWC in western Slovakia is expressed as a shear-zone (in the area of the CCA), as identified by section MT-15 (Bezák et al., 2014). The EP is represented here by the Cadomian complexes of Brunia (Dudek, 1980). A sudden change in the Moho depth at this contact in seismic (Hrubcová et al., 2010) and gravimetric (Bielik, 1995) models has been identified. The traces of early subduction became obscured by these youngest tectonic movements in a transpressional regime. The transpression is also associated with the formation of the younger fan structure of the KB.

Mainly orthogonal subduction and collision took place in the NE part of the WCp as shown by the primary position of KB, which became part of the FB accretionary wedge. Only in the final stages, when the subduction zone moved to the East Carpathians, did the the regime change to transpressional (e.g., Ratschbacher et al., 1993) accompanying reversing overthrusts and strike-slip faults alongside the KB (Plašienka et al., 2013).

These differences between the western and eastern parts of the WCp in the tectonic regime of the Neoalpine collision of the IWC and EP are also reflected in the internal structures of the IWC Block itself, which can be divided into two sub-blocks (Fig. 5).

The western sub-block is principally characterized by transpressional movements on mostly NE-oriented faults, shown in the tectonic scheme after Lexa et al. (2000) in Figure 5, which were activated during oblique collision. The most important shear zones with strike-slip movements include the tectonic zone at the margin of the EP, accompanied by the CCA, as well as other significant tectonic zones such as the Carpathian Shear Corridor (Marko et al., 2017) shown in Figure 6, and the zone around the KB itself with a typical flower structure. This structure was highlighted by the movements on normal faults in the subsequent transtensional stage. They are the primary cause of the formation of the so-called core mountains (horsts) and intramontane depressions (grabens) filled mainly with Neogene deposits (a "basin and range" structure). The transpressional movements also resulted in the emergence of Neogene basins (such as the Vienna and Orava basins) that overlap the original collisional zone and also the KB (Fodor, 1995; Ludwiniak et al., 2019).

The eastern sub-block of the IWC (Fig. 5) represents the part of the IWC that collided orthogonally with the EP in the NE part of the WCp Arc. In the structure of this block, there are no basin and range structures, but it contains compact embedded massifs such as the Veporské and Gemerské Rudohorie Mts. There are no significant Neogene faults, except for the N–S youngest faults (Branisko, Štítnik, Hornád; Fig. 6). Most strike-slip faults in this sub-block were active during previous stages of tectonic evolution (in Mesozoic and part of Late Paleozoic time; Bezák, 2002). An example is one of the most famous WCp faults, which is perhaps the most easily visible fault on satellite images. This is the Muráň Fault in the middle of the Veporic Massif, which has the character of a strike-slip fault of NE orientation (Pospíšil et al., 1989), which does not continue either into ICP strata to the NE nor into neovolcanic rocks to the SW.

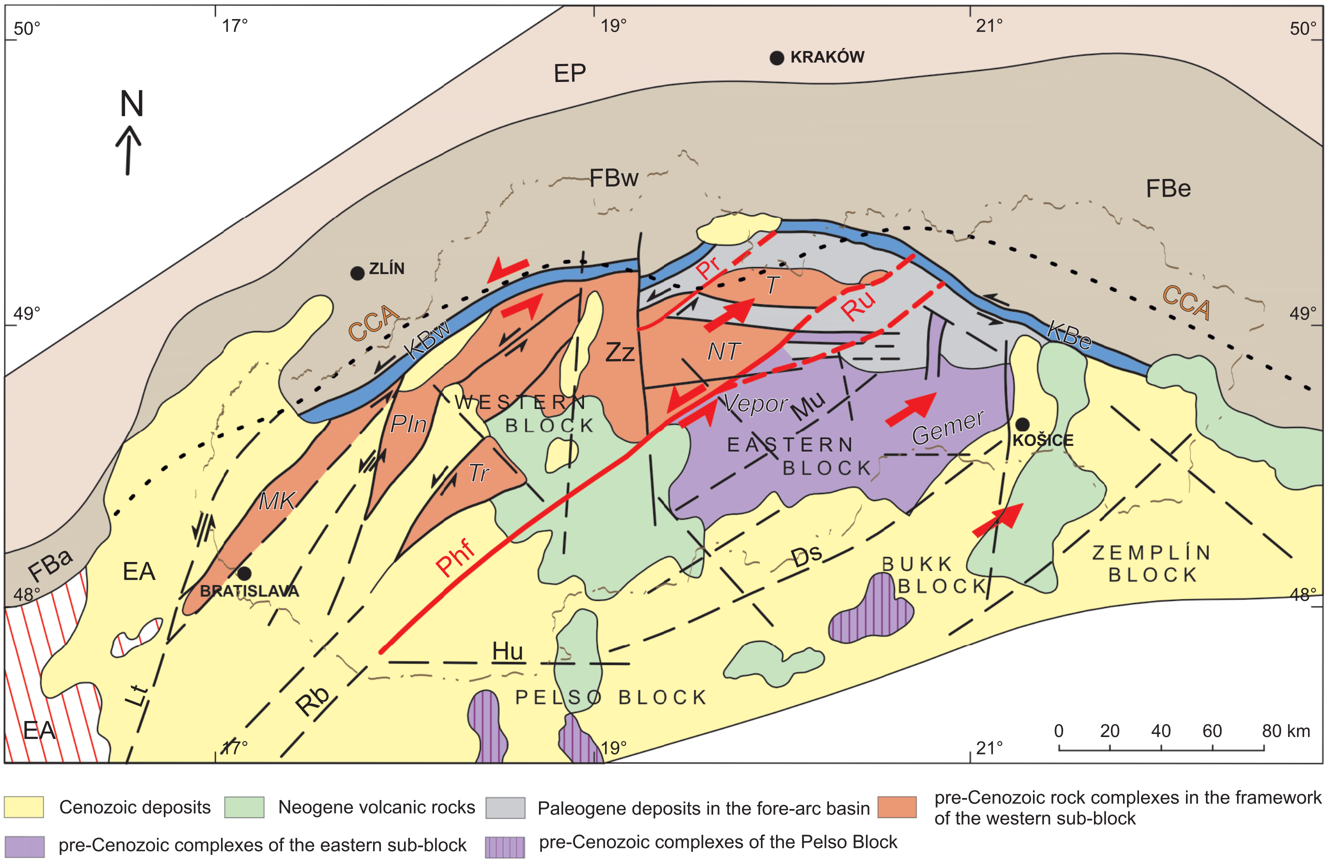

Fig. 5. Scheme of IWC tectonic sub-blocks and their relative movement during the Neogene (made with the use of the tectonic scheme of Lexa et al., 2000)

EP – European platform, FBw – western part of the Flysch Belt, FBe – eastern part of the Flysch Belt, FBa – Flysch Belt in the Alps, KBw – western segment of the Klippen Belt, KBe – eastern segment of the Klippen Belt, EA – pre-Cenozoic complexes in the Eastern Alps and in the Vienna Basin basement. Phf – Osrblie-Pohorelá shear zone. Faults: Rb – Raba, Hu – Hurbanovo, Ds – Diosjeno, Lt – Leitha, Zz – Zázrivá, Pr – Prosiek, Ru – Ružbachy, Mu – Muráň; CCA – position of the Carpathian Conductive Zone (Červ et al., 2001); some core mountains: MK – Malé Karpaty, PIn – Považský Inovec, Tr – Tríbeč, T – Tatry, NT – Nízke Tatry

The boundary between the western and eastern segments of the KB is probably located to the east of the Prosiek Fault (Pr), in the area where the Carpathian Arc direction changes. The marginal NE part of the western sub-block (to the SE of the Prosiek Fault; Fig. 5) was probably also involved in the orthogonal collision. This is also shown by the presence of a subduction root on the gravimetric model of this area (Dérerová et al., 2020). The change of tectonic regime in this part of the sub-block from transpression to collision was probably caused by a change in the geometry of the EP margin (from SW–NE to NW–SE orientation). In this part of the Fatra-Tatra sub-block, E–W faults are already developed (e.g., in the area of the Tatry Mts. and Vikartovce Ridge; Fig. 5), which together with the breaks in the N–S trending faults in the eastern sub-block are due to younger extension.

The position of strike-slip faults in the western segments is also visible on the gravimetric map of Bouguer anomalies (Pašteka et al., 2017; Fig. 6). The areas with highest Bouguer anomaly gradients on this map represent tectonic interfaces of blocks with different densities. These interfaces are in agreement with faults in the tectonic scheme in Figure 5, following Lexa et al. (2000). Many of the faults indicated are still active even today, as shown by the location of earthquake epicentres in the last two decades (Cipciar et al., 2020; Fig. 6). The depth of epicentres is not indicated, because they are not very well constrained and exhibit high uncertainty. It is significant that certain smaller activity on these faults persist till now. Generally, most of the epicentres are situated at depths of 1–15 km, and few of them are deeper than 20–25 km (these are situated near the Hurbanovo Fault, and near CSC faults). A similar pattern is shown by magnitude distribution, where the strongest earthquakes in the area studied are near the Hu, CSC, Pr and Phf faults (Fig. 6).

The greater extent of the collision in the NE of the WCp in the foreland of the Vepor-Gemer sub-block is reflected also by the disproportionately greater width of the FB compared to that in the western sector (see e.g., Lexa et al., 2000), and also by the typical large fore-arc basin of the ICP (Podhalie, Levočské vrchy Mts., Spišská Magura Mts.). Also, the character of volcanism may be evidence for this interpretation. Neogene volcanism in central Slovakia is connected to the evolution of the central astenolith beneath the Pannonian Basin and with the origin of the basin and range structure. By contrast, the volcanism in eastern Slovakia is associated with subduction (Konečný et al., 2002).

The Osrblie-Pohorelá Fault system (Phf in Figs. 5 and 6) was identified as a significant interface in the crust by geophysical modelling (Bezák et al., 2020) and it represents the boundary between the western and eastern sub-blocks. The Phf was a kind of transform fault system during Neogene subduction. It spatially follows the Rb Fault (Fig. 5), which divided mostly Eastern Alps pre-Cenozoic units from the Pelso Block. South of the eastern sub-block there are also other terranes of the Pannonian area which gradually became involved in the collision process with the EP (Pelso, Bukk and Zemplín blocks).

After subduction moved farther to the east (to the Eastern Carpathians), the KB, FB, and parts of the EP units together with the eastern part of the IWC became the upper plate in relation to subduction and entered a transtensional regime. This also al-

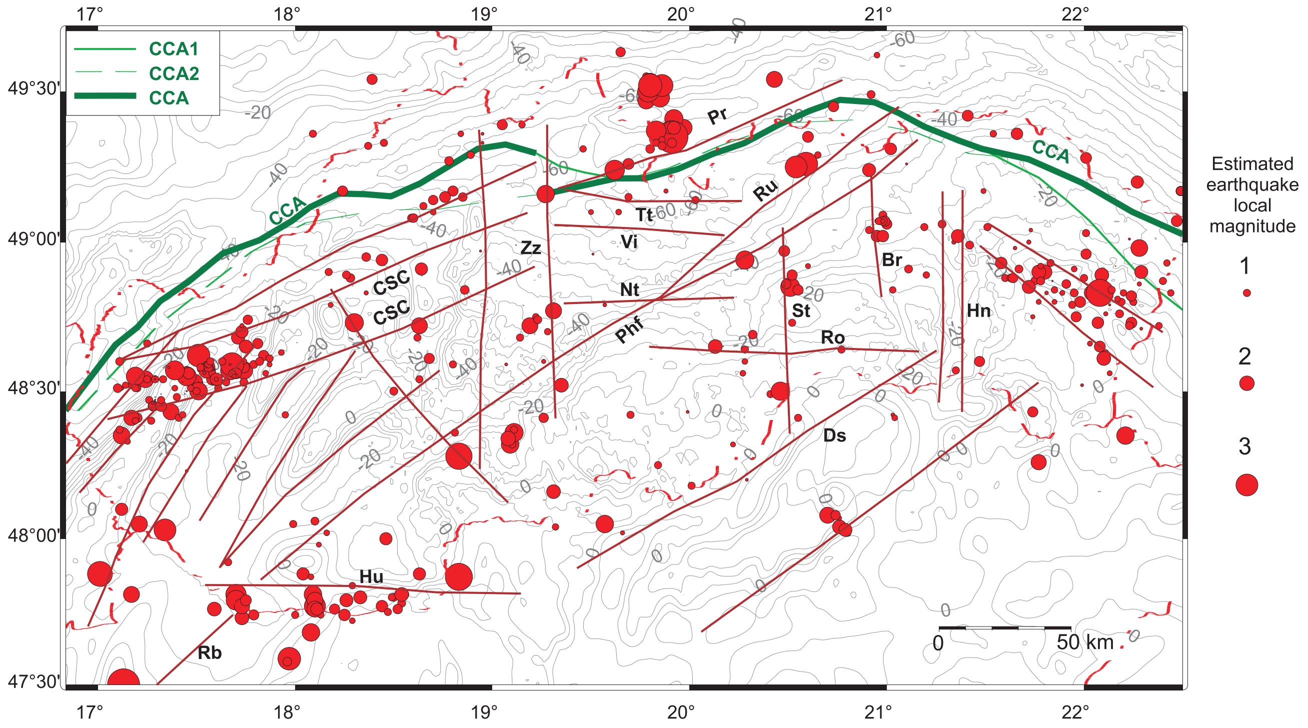

Fig. 6. Bouguer anomaly contour map of the area investigated, with epicentres of earthquakes during the last 20 years (after Cipciar et al., 2020)

Faults: Rb – Rába, Hu – Hurbanovo, Zz – Zázrivá, Pr – Prosiek, Tt – Tatry, Vi – Vikartovce, Nt – Nízke Tatry, Ru – Ružbachy, St – Štítnik Ro – Rožňava, Br – Branisko, Hn – Hornád, Ds – Diosjeno. The line labelled as CCA1 is the position of the CCA based on Jankowski et al. (1985), the CCA2 line follows Červ et al. (2001), and the CCA line is our interpretation; CSC – Carpathian shear corridor, Phf – Osrblie-Pohorelá shear zone lowed the penetration of volcanism described by e.g. Birkenmajer et al. (2004), Kucharič et al. (2013) to the north, beyond the former boundary of the subduction zone and north of the KB.

CONCLUSIONS

MT sounding in profiles across the western and eastern segments of the KB and OWC and IWC contact zone revealed important differences in their deep tectonic structures and thus also in the tectonic style in both segments. We infer the interface position between structures to the east from the Pr and Ru faults, where the orientation of the Carpathian Arc axis also changes. It would be appropriate to focus further geophysical research on this key area.

In the western segment, after a short period of subduction, oblique collision took place and a transpressional regime became dominant. The position of the KB in the backthrust to the south is attributed to a transpressional mode by most authors. We interpret that this position was inherited from the previous stage of subduction and early collision. This position was in many places subsequently reworked during the transpressional stage after subduction and collision moved into the eastern segment.

The eastern segment mainly experienced direct orthogonal subduction and collision and overthrusts of the FB accretionary prism to NE. FB thrusts also mostly include the KB units, which is in agreement with structural models described by earlier authors. Even these units were reworked in the southern part when the regime changed to transpressional.

Based on the different tectonic regimes in the western and eastern segments of the KB, we divide the IWC Block into two sub-blocks (Fig. 5). The differences of KB tectonic structures in the west and the east of the area studied, indicated by our MT models, are interpreted as different modes of these IWC sub-blocks' interaction with the EP. The western sub-block was mostly in an oblique collision mode with a predominantly transpressional regime, while the eastern sub-block was predominantly in orthogonal collision with thrusting tectonics to the NE. The dividing tectonic transformation zone between these sub-blocks was the Phf Fault system. This difference in tectonic regimes is also reflected in the internal structures of both sub-blocks.

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