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The Kolárovo gravity and magnetic anomaly body in a subcrop of the Danube Basin: A new geological interpretation

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Abstract: We provide an analysis of the existing 2D and 3D gravimetric and magnetic interpretations of the well-known and significant Kolárovo gravity and magnetic anomaly, as well as present a new geological interpretation of its origin. It follows that the source of these anomalies is a high-density and highly magnetic crustal body with the following parameters: (a) density contrast is between +0.28 and +0.31 g cm^{-3}, (b) magnetic susceptibility is ~22000×10^{-6} units of SI, (c) the depth of the upper boundary varies from ~4.5 to 6.0 km, (d) the depth of the center of the gravity body is between 8.7 and 12.5 km, and (e) the depth of the lower boundary moves in the interval from above 13 to 20 km. These factors and the inferred tectonic position of the Kolárovo body allow for its interpretation as a possible eclogite/ultramafite body. It occurs within a belt of magnetic and gravity anomalies tracing the Eo-Alpine high-pressure metamorphic complexes from the Eastern Alps to the Western Carpathians via the northern periphery of the Rába–Hurbanovo–Diósjenő fault zone. We assume that the position of the Kolárovo crustal body resulted from the Oligocene–Lower Miocene uplift of the East Alpine–West Carpathian junction caused by the compressional tectonic regime accompanied by crustal thickening, surface uplift, and erosion of units forming the present basement of the Danube Basin. Simultaneously, exhumation of the orogenic infrastructure occurred, which thus affected the Eo-Alpine metamorphic complexes, including the anomalous Kolárovo body. Subsequently, during the Middle–Late Miocene rifting and subsidence of the Danube Basin, the Kolárovo body was buried to its present position.

Keywords: Western Carpathians, Danube Basin, Kolárovo crustal body, applied geophysics, tectonic interpretation

Introduction

The Kolárovo gravity anomaly rightfully belongs to one of the most interesting features of the observed gravity field in the Western Carpathians of Slovakia. It is interesting not only because it represents a significant local gravity high located in the Danube Basin, but also because it can be observed in an area that is covered by a large thickness of low-density sediments. In other words, it is situated in an area where gravity low would be expected. This is also the reason why this anomaly was one of the first to be interpreted by Czech and Slovak geophysicists (e.g., Ibrmajer 1961). Therefore, due to its position and expression, the Kolárovo gravity high became an important geophysical anomaly which has been frequently quantitatively-interpreted in recent decades (e.g., Bielik et al. 2006; Kubeš et al. 2010; Zahorec et al. 2017, 2021). Despite this fact, its geological explanation has so far remained problematic.

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The Kolárovo gravity high (KGH) is located in the southern part of the Danube Basin, near the village of Kolárovo (Figs. 1, 2a, 3). The anomaly is of ellipsoidal shape with a longer semi-axis in the W–E direction, and it reaches a magnitude of about +14 mGal (1 mGal=10 μm/s^2). Its peculiarity lies in the fact that in the area where the anomaly is located, it is not accompanied by any significant geological structure that could explain its origin. Interestingly, it occurs in a deeper substratum of the Neogene sediments of the Danube Basin, which reaches a thickness of 2.3 to 3.7 km (Fusán et al. 1987, 1971; Šefara et al. 1987). The boreholes Kolárovo 2 (K2), 3 (K3), and 4 (K4) around the anomaly detected the basement at the depths of 3050, 2690, and 2640 m, respectively (Gaža 1966, 1967, 1970). According to borehole data, the basin subcrop is composed of granitoid rocks and crystalline schists of the Variscan basement now included in the Alpine Veporic tectonic unit.

It is surprising that, compared to the complete Bouguer anomaly map, no such significant anomaly can be seen on the map of the total vector of the magnetic field in the Danube Basin (Fig. 4; Kubeš et al. 2010). In contrast, several local positive magnetic elevations can be observed in the vicinity

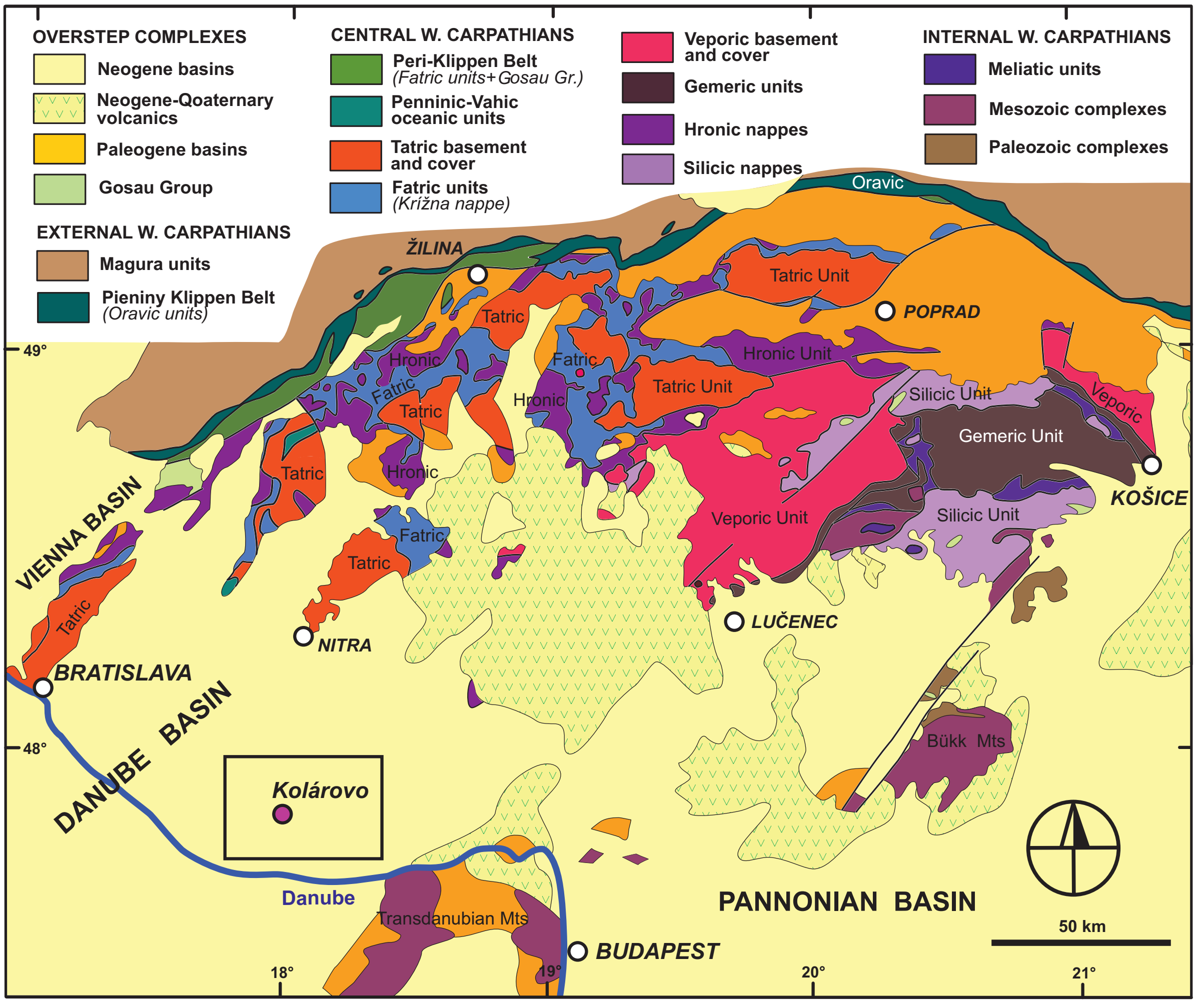

Fig. 1. Simplified tectonic map of Western Carpathians; the rectangles indicate the position of the examined area.

of Kolárovo, which stretch across the northern part of the Gabčíkovo depression from west to east. According to Kubeš et al. (2010), these anomalies are likely due to the Tatricum crystalline complex or the Cadomian basement. Obviously, the source of these anomalies may be in mafic rocks complexes, because heavy masses are detected in this area. Other sources could be rocks that were formed by basic differentiates of granitoids or diorites. According to Kubeš et al. (2010), in some cases, the sources of magnetic anomalies could also be mafic remnants of the Meliatic unit inside the suture zone, which was utilized for partial raising of the asthenolith body during the extension process in the Neogene.

However, Prutkin et al. (2011, 2014) discovered that the Kolárovo magnetic high (KMH) is clearly visible only after removing the regional field and signal of shallow sources down to the depth of 2.5 km (Fig. 5). In such a case, the residual KMH already coincides very well with the KGH (Prutkin et al. 2014; Fig. 5).

With regards to their importance, the interpretation of both KGH and KMH has been of great interest to geophysicists and geologists. Identification of sources of these anomalies is extremely important for the understanding of the tectonic evolution of not only the Western Carpathians, but of the entire Alpine–Carpathian orogenic belt as well. Therefore, we propose a new tentative interpretation of their possible sources and structural position within the Eastern Alpine–Western Carpathian junction area.

Geological background

The anomalous Kolárovo body occurs in the trasitional Alpine–Carpathian region, which is largely covered by superimposed Neogene basins of the Pannonian Basin system, namely the large-scale Danube Basin (Fig. 1). Consequently, direct information about the composition and tectonic affiliation of pre-Neogene basement complexes are only obtainable from a limited number of deep boreholes, and indirectly from interpretation of the geophysical potential fields. The available data and the regional tectonic considerations indicate that units occurring in the Danube basin substratum belong to the Austroalpine tectonic system, which are exposed in quite

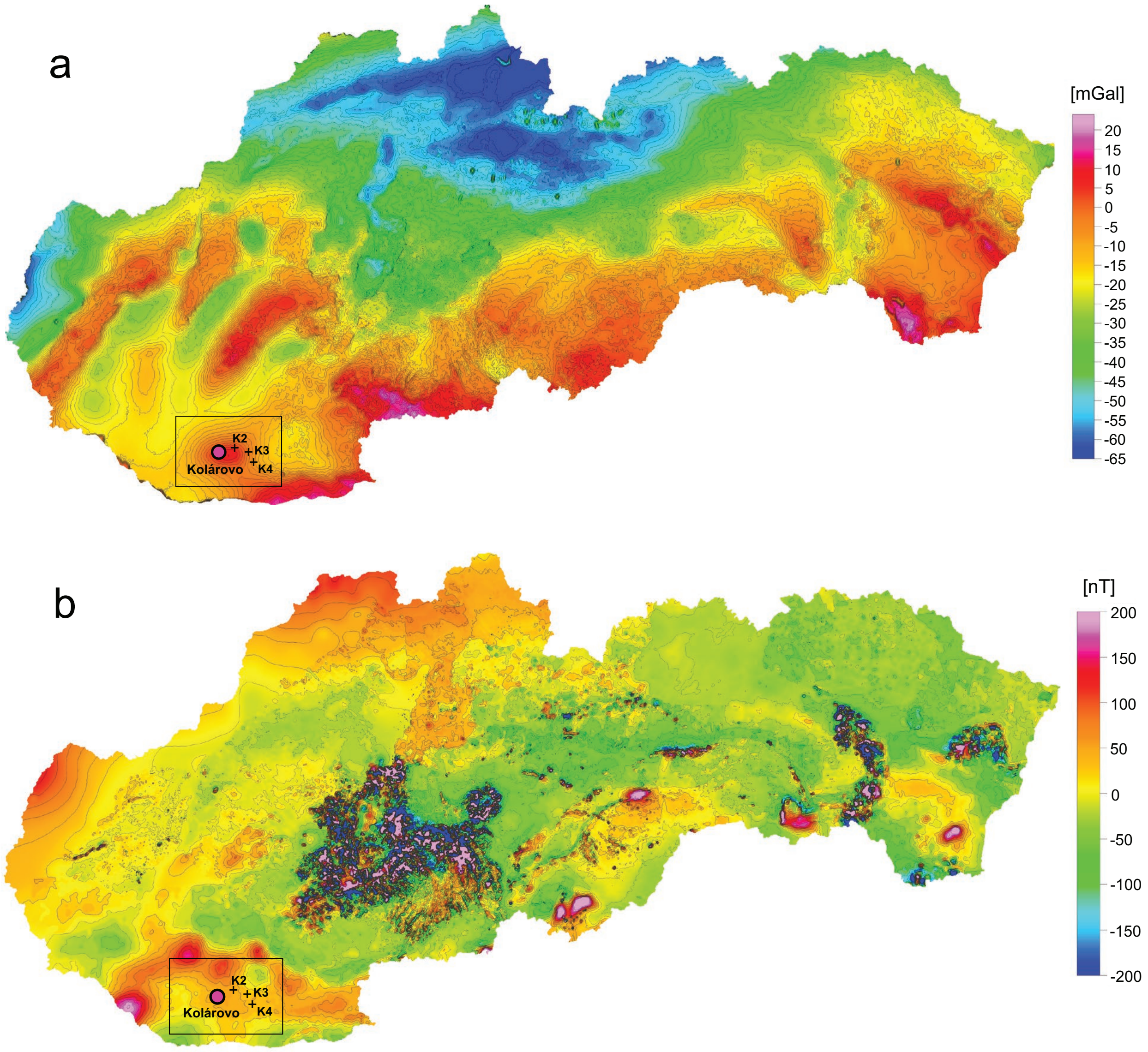

Fig. 2. a — Complete Bouguer anomaly map of Slovakia (after Zahorec et al. 2017); **b** — Magnetic anomaly map of Slovakia (after Kubeš et al. 2010); K2, K3 and K4 – boreholes Kolárovo 2, 3 and 4.

remote places in the Central Eastern Alps to the west and the Central Western Carpathians to the east (e.g., Schmid et al. 2008). The Austro-alpine system was dominantly formed by the early Alpine (Eo-Alpine, Cretaceous) tectonic stacking prograding northwards from the collisional zone after closure of the Meliata Ocean in the south (e.g., Plašienka 2018). It includes both the detached cover nappe system and the thick-skinned, crustal-scale thrust sheets. In the Eastern Alps, the cover nappes that are predominantly composed of Mesozoic rocks are accumulated in the Northern Calcareous Alps, while the pre-Alpine basement complexes with remnants of their sedimentary cover build up large areas of the Central Eastern Alps as far as the west-east trending Peri-Adriatic fault zone, thereby forming the boundary with the Southern Alps. This configuration is mainly due to the superimposed Paleogene collisional processes and exhumation after closure of the Ligurian–Piemont oceanic domain (Alpine Tethys, resp. Alpine Atlantic) between the Austro-alpine domain (part of the Adria microcontinent) and the North-European Platform. In the Central Western Carpathians, the Cretaceous basement and cover nappe edifice is largely preserved thanks to the eastward lateral escape of the Alpine-Carpathians-Pannonia terrane (AlCaPa) from the Alpine collision (Ratschbacher et al. 1991; Sperner et al. 2002). As a result, the Central Eastern Alps expose deep-seated basement complexes affected by high-grade Eo-Alpine metamorphism, whereas only a moderate Cenozoic exhumation affected the Central Western Carpathians. According to Kováč et al. (2016), the Hurbanovo–Diósjenő fault zone formed a pre-Oligocene eastward continuation of the Peri-Adriatic fault, which was later offset

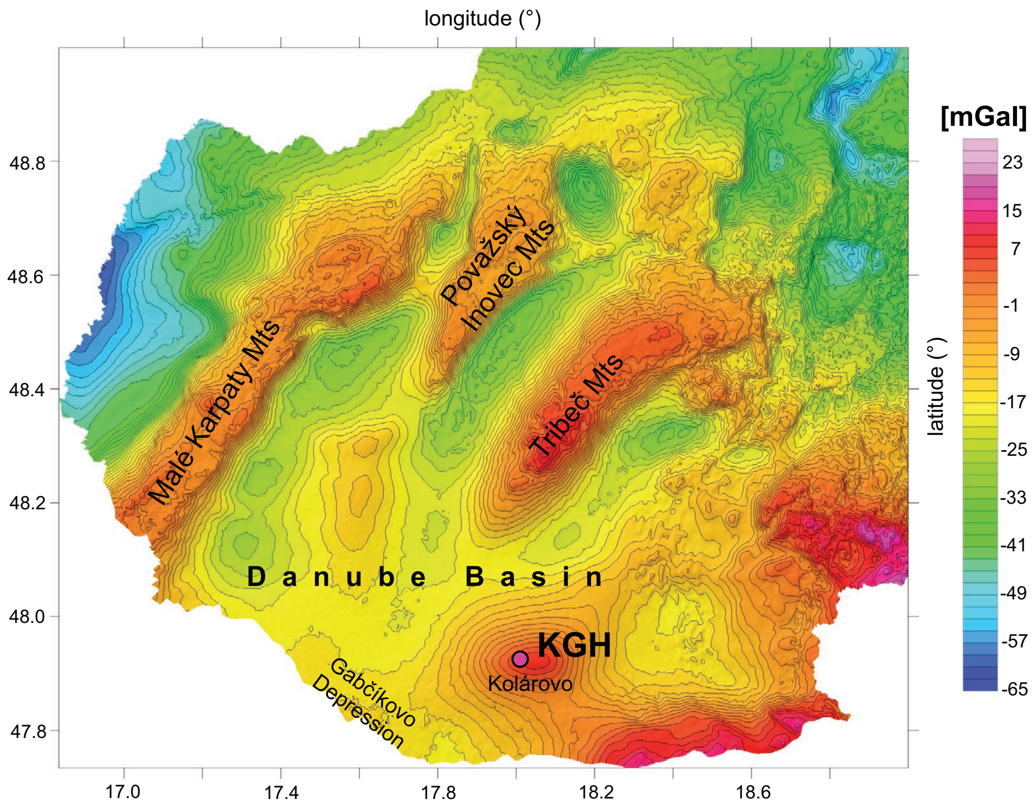

Fig. 3. The complete Bouguer anomaly map (modified after Zahorec et al. 2017). KGH – Kolárovo Gravity High.

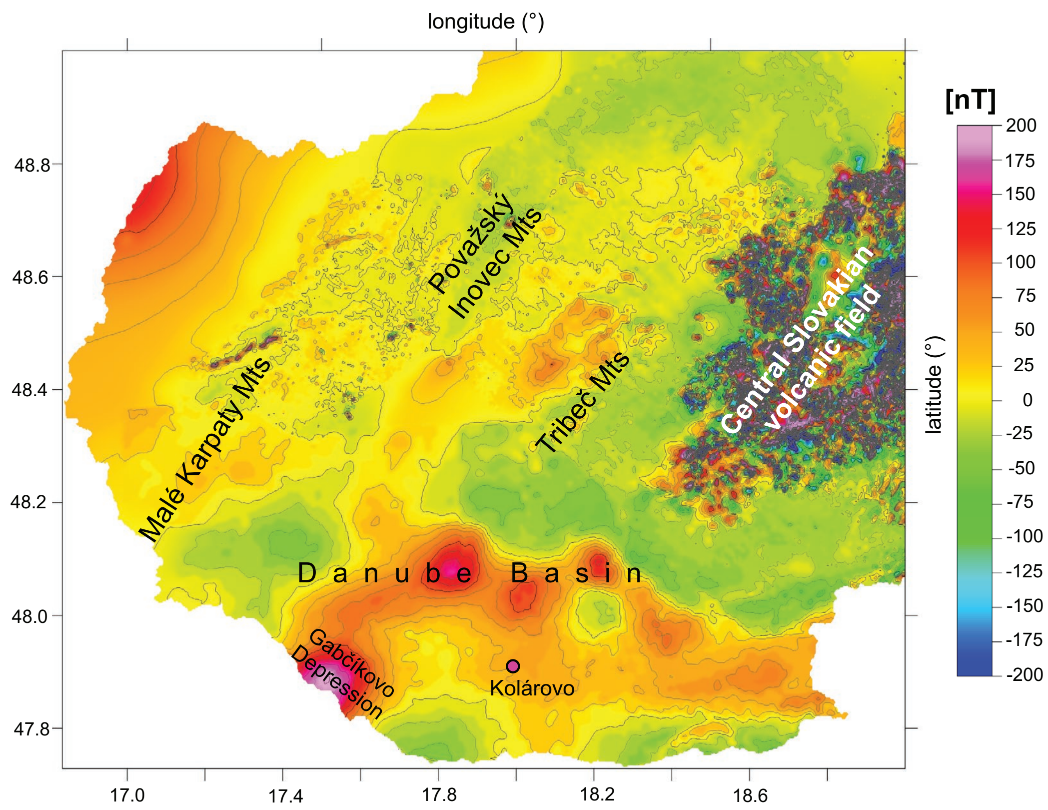

Fig. 4. The total vector of magnetic intensity map (modified after Kubeš et al. 2010).

by the SW–NE trending Rába fault zone. Accordingly, the Transdanubian Range unit (a.k.a. the Pelso block) occurring south of the Rába–Hurbanovo–Diósjenő fault zone may be considered as the eastern prolongation of the South-Alpine units into the Carpathian area, which is known as the Pelso Megaunit.

Geophysical interpretations of the Kolárovo gravity and magnetic anomaly body

The first qualitative interpretation of the KGH was made by Ibrmajer (1961), who assumed that its source is a high-density body located in the lower layers of the sedimentary fill of the Danube Basin. This interpretation was not confirmed, since the boreholes Kolárovo-2, 3, 4 (Gaža 1966, 1967, 1970), which reach the pre-Cenozoic basement, did not find any high-density body in the sedimentary fill.

Since the beginning of the 1970s, several quantitative (inverse) interpretations of the KGH and KMH have been carried out. Despite the fact that the 2D and 3D inverse interpretations of gravity (Fusán et al. 1971, 1987; Bielik 1984; Sitárová et al. 1984, 1994; Bielik et al. 1986; Šefara et al. 1987; Šefara & Szabó 1997; Vajda et al. 2002) and magnetic fields (Kubeš et al. 1989; Valach & Váczyová 1999; Prutkin et al. 2011, 2014) indicated different geometric shapes of this body, its quantitative parameters seem to be quasi-uniform and can be generalized as follows:

- Density contrast varies from above +0.28 up to +0.31 g cm^{-3} (1 g cm^{-3} = 1000 kg m^{-3});
- Magnetic susceptibility ~22000×10^{-6} units of SI;
- Upper boundary is located at a depth of ~4.5–6.0 km;
- Depth of the centre of mass of the body is ~8.7–12.5 km;
- Lower boundary moves in the interval from above 13 to 20 km.

In general, this means that the source of the KGH and KMH represents a high-density and high-magnetic anomalous body located mainly in the upper crust.

Overview of geological interpretations of the Kolárovo anomalous crustal body

Sitárová et al. (1984) believed that the source of the KGH is a body that was formed by the process of basification of the upper crust. According to the interpretation given by Kubeš et al. (2010, anomaly N4), the Kolárovo magnetic high was likely caused by mafic remnants of the Meliaticum oceanic crust inside a suture zone, along which asthenolithic melts rose at an angle. The rise of the modified lower crust or asthenosphere material was facilitated by an extension process during the formation of the Danube Basin (Prutkin et al. 2014).

However, the inversion results of Prutkin et al. (2014) do not indicate any asthenolith or mafic remnants in a slanted position under an angle as indicated by Bezák et al. (1997). For this reason, they interpreted possible geometric shapes of

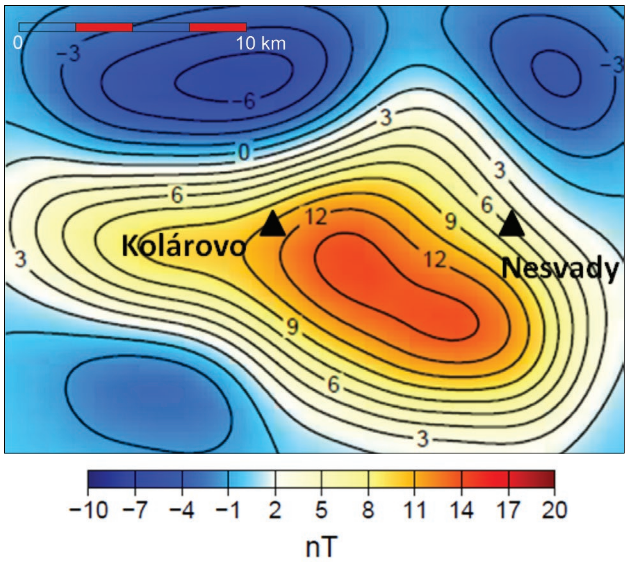

Fig. 5. Residual Kolárovo magnetic anomaly calculated by the stripping method (Prutkin et al. 2014).

the Kolárovo anomalous crustal body in three different ways: (1) according to the most likely explanation, the suture only served as a low-resistance path for the rising magma, while the intrusion which originated shows no slanted shape; (2) a combination of an elevation of the upper/lower crust boundary and a mafic intrusion into the felsic upper crust above it; (3) an isolated, heavy, and compact anomalous body (the least probable interpretation). From a tectonic point of view, Bezák, in Prutkin et al. (2014), emphasizes that the location of the Kolárovo anomalous body is located near the Rába–Hurbanovo–Diósjenő fault system, which separates two different tectonic systems: the Eastern Alpine–Western Carpathian (Austroalpine) in the north and the Pelso Unit in the south.

It turns out that, unlike the geophysical interpretation, the geological explanation for the existence of the Kolárovo crustal body in the south of the Danube Basin is problematic and still open. Therefore, its new alternative geological interpretation is presented here.

New interpretation of the Kolárovo gravity and magnetic anomaly body

As it follows from the above data, the interpretations of the KMH and KGH are quite variable, which results from the lack of first-order data. Since the source of the anomaly lies at comparatively deep levels of the upper-to-middle crust and was never reached by deep boreholes, its geological position is not known from direct data. Most of the proposed interpretations regard a probably Miocene intrusion of a high-density magmatic body, as being the anomaly source. The geophysical characteristics would require a mafic or ultra-mafic intrusion.

However, the late Cenozoic Central Slovak volcanic field east of the Danube Basin (Fig. 1), as well as volcanic edifices buried on the basin's bottom (e.g., Rybár et al. 2024), are predominantly composed of intermediate calc-alkaline volcanic rocks, while the youngest alkaline basalts may form only small lava flows or perhaps thin dykes in the basement, which are not capable of producing such a strong anomaly. Therefore, the Neogene magmatic intrusion as a source of the KMH and KGH is considered unlikely.

Hereafter, another possible source of the KGH and KMH is proposed. According to the pre-Cenozoic basement maps of the Danube Basin, the Kolárovo body should be located within the pre-Alpine crystalline basement complexes of the southern Veporic zones (e.g., Fusán et al. 1987; Horváth 1993; Plašienka et al. 1997; Császár et al. 2000; Hók et al. 2016a, b; Kováčik 2018). The Veporicum is a crustal-scale basement wedge, the middle of three that constitute the crustal profile of the Central Western Carpathians – it overrides the Tatric thick-skinned thrust sheet that is overthrust by the Gemeric low-grade metamorphic units (e.g., Plašienka 2018 and references therein). Cropping out on the surface farther east, the southern Veporic zones were affected by the medium-pressure and medium-temperature Eo-Alpine (Cretaceous) metamorphism, which reached the amphibolite facies conditions in the deepest exposed basement unit (Janák et al. 2001; Jeřábek et al. 2008, 2012). The identical metamorphic complexes were encountered by boreholes reaching the pre-Neogene basement north of the Diósjenő fault zone in Northern Hungary (Koroknai et al. 2001).

In the Eastern Alps, the Eo-Alpine metamorphism reached eclogite facies conditions and affected the large basement complexes of the Lower Central Austroalpine units (e.g., Froitzheim et al. 2008; see EAHPB – Eastern Alpine High Pressure Belt in Fig. 8) in a similar tectonic position like the Veporic units. In the most exhumed Austro-alpine units at the south-eastern extreme of the Eastern Alps, in the Pohorje Mts of Slovenia, the Eo-Alpine metamorphism attained ultra-high pressure (UHP) conditions, which were revealed by diamond-bearing paragneisses, eclogites, and garnet peridotites (Janák et al. 2004, 2006, 2015; Kirst et al. 2010). In the south-eastern part of the Pohorje Mts, metaultramafic rocks form a large, 8×9 km^2 body – the Slovenska Bistrica Ultramafic Complex (SBUC; Janák et al. 2006). SBUC comprises serpentinized harzburgite, garnet peridotite, garnet pyroxenite, and kyanite eclogite (Janák et al. 2006; De Hoog et al. 2009). Assuming the metamorphic field gradient and the Cretaceous age of the peak metamorphism, which are well-documented in the Eastern Alps (e.g., Miladinova et al. 2022) and less so in the Veporicum (e.g., Janák et al. 2001), we suppose that the Veporicum may be an eastern continuation of the Austro-alpine EAHPB, though the surface exposures of the Veporicum experienced only amphibolite-facies metamorphism. According to Balla (1994a, b), the KGH occurs within a belt of magnetic anomalies (see BGHMH in Fig. 8) that stretches southwestward along the NW periphery of the Rába fault zone (RFZ) up to the south-eastern corner of the Eastern Alps in the Pohorje Mts. Hence, this zone connects the Eo-Alpine UHP rock complexes of the Pohorje Mts with the KGH and indicates their possible links. It has been correlated with the EAHPB by Schmid et al. (2008) as well. Therefore, the correlation of sources of the KGH and KMH with the Eo-Alpine eclogite to UHP complexes seems to be a plausible solution.

The presented hypothesis is supported by the geophysical data. First of all, gravimetric data must be included (e.g., Bielik et al. 2006; Meurers & Ruess 2009; Medved et al. 2021; Zahorec et al. 2021). When we look in detail at the complete Bouguer gravity anomaly map (Fig. 6), we clearly observe that the entire area stretching southwest from the KGH through the Mihályi zone to the Pohorje Mts is accompanied by the belt of positive gravity highs (BGH). We assume that this gravity anomalous belt reflects the gravity effects of high-density rocks building the Eo-Alpine HP–UHP complexes. In Bielik et al. (2006), Meurers marked out this anomalous belt as belonging to the Eastern Alpine units. Based on the calculated stripped gravity maps (e.g., Meurers & Ruess 2009; Bielik et al. 2022) and the Ellipsoidal Bouguer anomaly map of Slovenia (Medved et al. 2021), it can be assumed with great likelihood that the rocks of the high-grade Eo-Alpine metamorphism may also occur in the structure of the pre-Cenozoic basement in the Mura Basin, Zala Basin, Mihályi Zone, and central part of the Danube Basin.

Secondly, the Eo-Alpine HP–UHP complexes are also well-traceable on the magnetic anomaly map of total intensity of a geomagnetic field (Grabowska et al. 2011). On this map (Fig. 7), we indicate the noticeable belt of magnetic highs. We believe that the magnetic highs are due to the rocks of the Eo-Alpine metamorphic complexes. Moreover, based on the map of vertical component magnetic anomalies in Slovenia (Gosar 2005), we suggest that the anomalous magnetic belt could continue further west to the Pohorje Mts.

The Veporic metamorphic dome exposed at the surface in Central Slovakia (Fig. 8) was exhumed by crustal thickening due to the basement thrust stacking and ensuing orogen-parallel extension and unroofing of the overlying Gemeric and higher nappe units as early as the latest Cretaceous and earliest Paleogene (Králiková et al. 2016; Vojtko et al. 2016) and was not affected by a considerable exhumation later. In contrast, the final exhumation of the Eo-Alpine high-pressure belt occurred following the Eocene Adria–Europe collision during the late Cenozoic, lithospheric-thickening formation of the high mountainous relief and eastward extrusion of the Austroalpine units (e.g., Fodor et al. 1998, 2008). As a result, the extension and erosion-related exhumation in the Alps reached the deep-seated amphibolite to eclogite facies rock complexes, which are likely still hidden in the lower–middle crustal levels of the exposed southern Veporic zones.

According to available drillhole data, the basement substratum of the central part of the Danube Basin is uniformly composed of crystalline basement complexes and devoid of the Mesozoic cover and nappe units. This indicates that this area was affected by important exhumation as well, which was likely caused by compression-related crustal thickening before

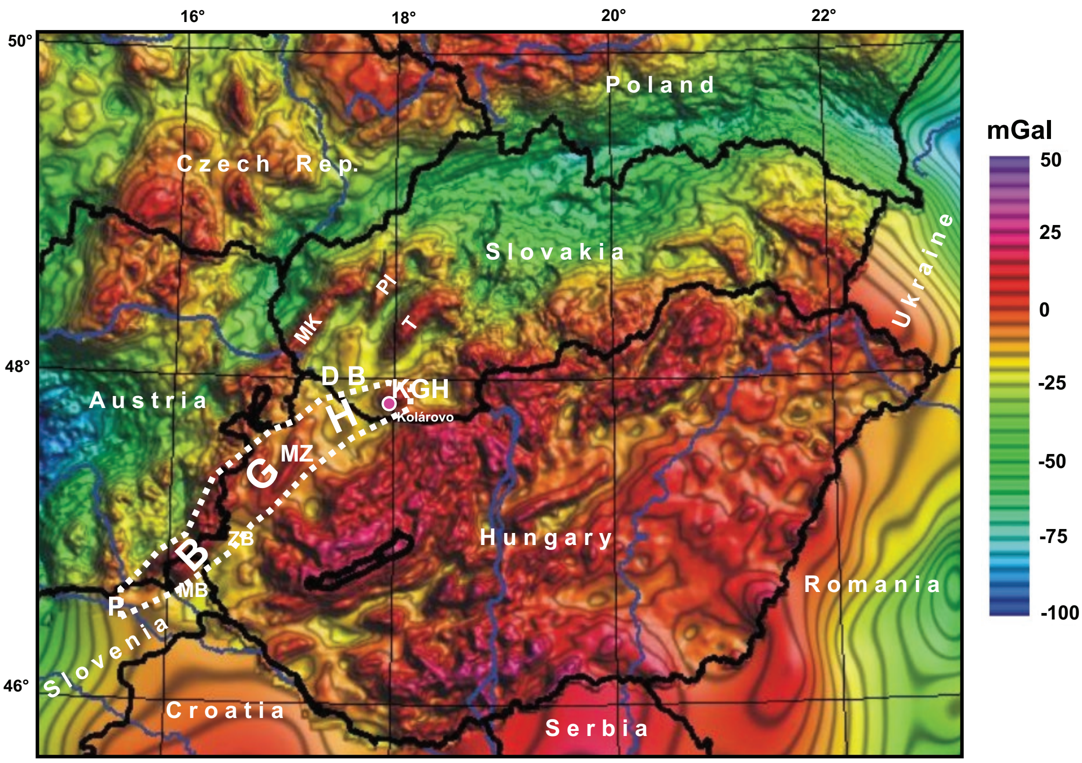

Fig. 6. The complete Bouguer gravity anomaly map of Central Europe (modified after Bielik et al. 2006). KGH – Kolárovo gravity high; BGH – Belt of Gravity Highs; MZ – Mihalyi zone; ZB – Zala Basin; MB – Mura Basin; P – Pohorje Mts; MK – Malé Karpaty Mts; PI – Považský Inovec Mts; T – Tribeč Mts; DB – Danube Basin.

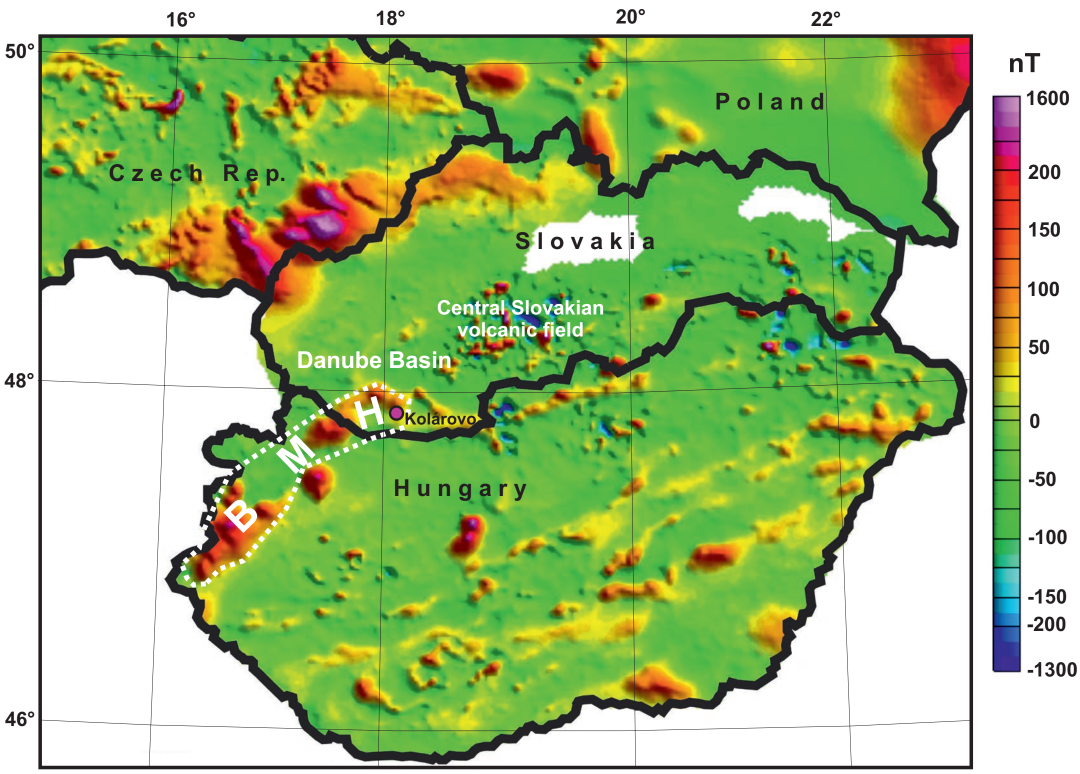

Fig. 7. Magnetic anomaly map of total intensity of geomagnetic field (modified after Grabowska et al. 2011). BMH – Belt of Magnetic Highs.

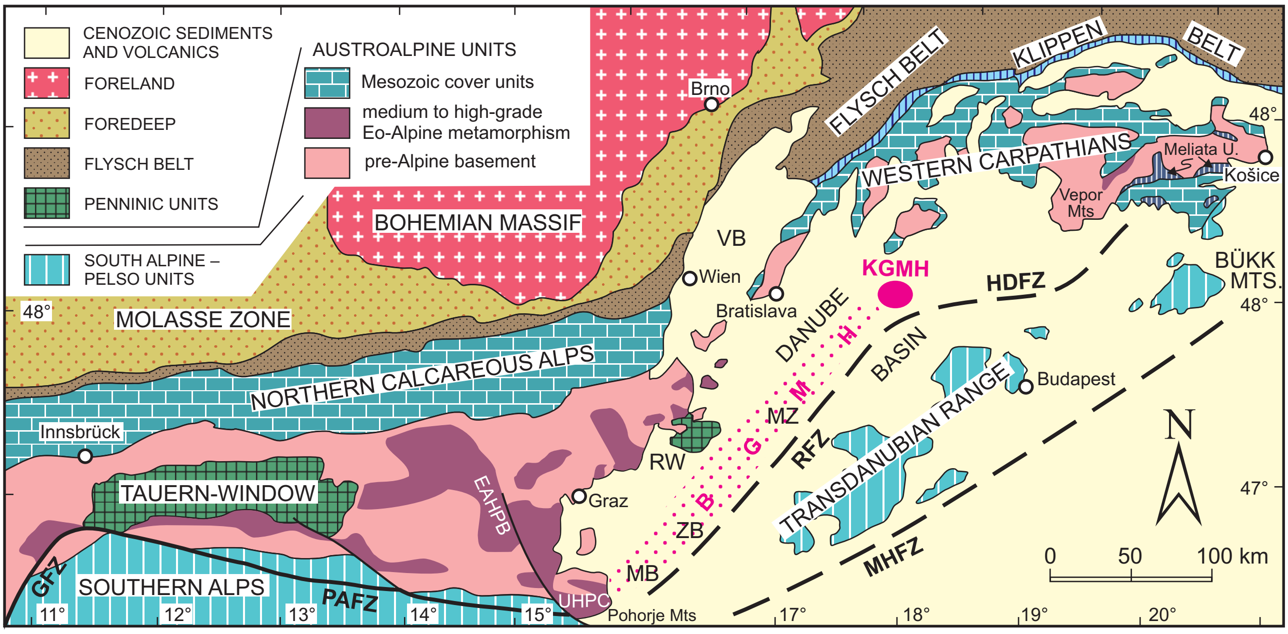

Fig. 8. Tectonic sketch map of the Eastern Alps and Western Carpathians with position of the subsurface Kolárovo gravity and magnetic high (KGMH) in relation to the Eo-Alpine high-pressure belt (EAHPB) and ultra-high pressure complex (UHPC) in the Pohorje Mts. BGMH – belt of gravity and magnetic highs; MB – Mura Basin; ZB – Zala Basin; VB – Vienna basin; MZ – Mihályi zone; RW – Rechnitz window; PAFZ – Peri-Adriatic fault zone; MHFZ – Mid-Hungarian fault zone; GFZ – Giudicarie fault zone; RFZ – Rába fault zone; HDFZ – Hurbanovo–Diósjenő fault zone.

the main phase of extension and subsidence of the Danube Basin during the Middle Miocene (Hók et al. 2016a; Kováč et al. 2016, 2017; Šujan et al. 2021; Tari et al. 2021). In the Alpine–Carpathian junction zone, the eastward extrusion/escape of the AlCaPa (Alps–Carpathians–Pannonia; e.g., Ratschbacher et al. 1991; Sperner et al. 2002) tectonic assembly was accompanied by extensional exhumation of Penninic oceanic units exposed in the Rechnitz window group (RW in Fig. 8). Tentatively, owing to the presence of ophiolitic rocks, the Penninic rock complexes could also be considered as possible sources for gravity and magnetic anomalies (Balla 1994a). However, their expression in the potential fields is rather weak, and the Rechnitz window generally occurs outwards, though nearby, the belt of the gravity and magnetic highs under question (BGMH in Fig. 8). Moreover, as pointed out also by Prutkin et al. (2014), the tectonic situation of Penninic rocks in the Rechnitz window and sources for the BGMH appear to be different – the former were exhumed from below the lowermost Austro-alpine units during the Middle Miocene (Dunkl & Deményi 1997), whereas the latter occur in an upper structural position within the higher Austro-alpine basement units (Lower Central Austroalpine–Veporic).

Discussion

Hence, the tectonic scenario proposed herein considers a Late Eocene–Oligocene compressional regime in the future Danube Basin, which produced a thickened crust composed of a thick-skinned thrust stack. This thrust stack included, from the bottom to top and from north to south: (1) the lower crustal imbricated antiformal duplex of the European foreland basement (Danubius Antiform of Tari et al. 2021) or the Oravic basement slivers (Czorsztyn Ridge, Plašienka et al. 2020); (2) the Tatric basement/cover sheet possibly underlain by the Middle Penninic basement slivers and Upper Penninic nappes, such as those exposed in the Rechnitz window; (3) the Veporic basement wedge affected by the Eo-Alpine pressure-dominated metamorphism; (4) upper Austroalpine décollement cover nappes (Fatric, Hronic); and (5) Lower Paleozoic low-grade volcano-sedimentary complexes (e.g., Mihályi complex) overlain by the Mesozoic successions of the Transdanubian Range. It should be noted that the Tatric basement/cover sheet, despite being in the Lower Austroalpine position, only occurs north of the latitude of the Hurbanovo–Diósjenő fault zone, i.e., it is a typical Western Carpathian unit having no direct analogues in the Alps (e.g., Plašienka 2018). Throughout the pre-Oligocene convergence, the Rába and Hurbanovo-Diósjenő fault zones (RFZ and HDFZ) likely formed an eastern splay of the Peri-Adriatic fault zone (PAFZ; Fig. 8) with a minor lateral displacement (e.g., Kováč et al. 2016). During the subsequent Oligocene collision stage of the Alpine–Carpathian orogenic wedge with the European continental plate, the thickened wedge overrode the southeastern spur of the Bohemian Massif. Crustal stacking led to erosional and/or extensional removal of Mesozoic cover over nappe units in the present substratum of the Danube Basin, as well as exhumation of deep crustal Eo-Alpine metamorphic complexes (including the Veporic Kolárovo body).

Finally, the Middle Miocene rifting and ensuing thermal subsidence created an accomodation space for deposition of thick Upper Miocene to Quaternary sedimentary formations of the Danube Basin (e.g., Šujan et al. 2021), which burried the Austro-alpine to deeper crustal levels once more.

Conclusions

The Kolárovo body represents a distinct gravity and magnetic high occurring in the substratum of the thick Neogene deposits of the Danube Basin in the Alpine–Carpathian junction area. According to the borehole-based pre-Neogene subcrop maps, the body is situated within the Veporic basement complexes, which are affected by the Eo-Alpine (Cretaceous) greenschist to amphibolite-facies metamorphism. It was modelled as a slightly elongated form located in the middle and upper crust at depths between 4.5–6 and 13–20 km. We have presented a tentative interpretation of the anomaly source that had not been considered previously. The Kolárovo body occurs within a belt of gravity and magnetic anomalies that follows the northern periphery of the Rába–Hurbanovo fault zone connecting the Eo-Alpine high-pressure belt of the Eastern Alps with the Carpathian Veporic basement complexes. In particular, we assume that the Kolárovo body might be composed of similar (ultra)-high pressure metamorphics, eclogites, and garnet peridotites like those of the Slovenska Bistrica Ultramafic Complex exposed in the Pohorje Mts at the south-eastern extremity of the Eastern Alps.

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