

Joint interpretation of gravity and magnetic data in the Kolárovo anomaly region by separation of sources and the inversion method of local corrections

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Abstract: We present a new interpretation of the Kolárovo gravity and magnetic anomalies in the Danube Basin based on an inversion methodology that comprises the following numerical procedures: removal of regional trend, depth-wise separation of signal of sources, approximation of multiple sources by 3D line segments, non-linear inversion based on local corrections resulting in found sources specified as 3D star-convex homogenous bodies and/or 3D contrasting structural contact surfaces. This inversion methodology produces several admissible solutions from the viewpoint of potential field data. These solutions are then studied in terms of their feasibility taking into consideration all available tectono-geological information. By this inversion methodology we interpret here the Kolárovo gravity and magnetic anomalies jointly. Our inversion generates several admissible solutions in terms of the shape, size and location of a basic intrusion into the upper crust, or the shape and depth of the upper/lower crust interface, or an intrusion into the crystalline crust above a rise of the mafic lower crust. Our intrusive bodies lie at depths between 5 and 12 km. Our lower crust elevation rises to 12 km with and 8 km without the accompanying intrusion into the upper crust, respectively. Our solutions are in reasonable agreement with various previous interpretations of the Kolárovo anomaly, but yield a better and more realistic geometrical resolution for the source bodies. These admissible solutions are next discussed in the context of geological and tectonic considerations, mainly in relation to the fault systems.

Key words: Western Carpathians, Danube Basin, intrusion, applied geophysics, gravity, magnetic field, Kolárovo anomaly.

Introduction

The Danube Basin displays peculiar anomalies in the gravity and magnetic fields that are supposedly associated with deep seated sources within the pre-Neogene basement (Kubeš et al. 2001, 2010). According to Kubeš et al. (2010) the interpretations of these sources are insufficient and problematic and thus remain open for further investigation. Here we present a new interpretation of both the Kolárovo gravity anomaly (gravity high) and the Kolárovo magnetic anomaly (anomaly “N4” in Kubeš et al. 2010) by means of a 3D inversion of gravity and magnetic data based on depth-wise separation of sources and the so-called “method of local corrections”. This non-linear inversion method can invert gravity or magnetic data in terms of interface (contact) surfaces or anomalous source bodies, as well as a combination of these two classes of sources. The inversion yields several admissible solutions — admissible from the viewpoint of potential field data. This is the strength and advantage of the method: the interpreter has at hand a multitude — a set — of model solutions that satisfy the observed surface potential data and can take a look at them from the viewpoint of constraining information, if available from other earth science disciplines.

Additional geophysical or other geoscientific data can be used, such as geological and tectonic, to discriminate between these admissible solutions, and to favour the likely and most realistic one.

The Kolárovo gravity anomaly (high) is located in the south-eastern part of the Danube Basin, in the northern part of the Pannonian Basin, near the village of Kolárovo, southern Slovakia (Fig. 1). The anomaly is one of the largest and most famous gravity highs in the Western Carpathian-Pannonian area. Therefore it has been of great interest to geophysicists and geologists since the early 1960s. In terms of complete Bouguer anomaly the Kolárovo high is fairly isometric and reaches a magnitude of +28 mGal (1 mGal = 10 $\mu\text{m/s}^2$). After removing the gravitational effect of the sedimentary basin fill, the gravity high in terms of a stripped Bouguer anomaly has an amplitude of +74 mGal, which, relative to the ambient field, amounts to some +26 mGal (Bielik et al. 1986).

According to the existing geological and geophysical results (Gaža 1966, 1967, 1970; Fusán et al. 1971, 1987; Bielik 1984; Sitárová et al. 1984, 1994; Bielik et al. 1986; Šefara et al. 1987; Šefara & Szabó 1997), the Kolárovo gravity high indicates the existence of a higher-density mafic (basic) anomalous body within the Pre-Tertiary basement of the

southern part of the Danube Basin. In the Kolárovo anomaly region and its vicinity the Neogene sediments reach a thickness of 2.3 to 3.7 km (Fusán et al. 1987; Šefara et al. 1987). The boreholes Kolárovo 2, 3, and 4 around the anomaly detected the basement at the depths of 3050, 2690, and 2640 m, respectively (Gaža 1966, 1967, 1970). The basement is made up of granitoid rocks and crystalline shists of the Hercynian basement now included in the Veporicum Alpine tectonic unit. In the Kolárovo anomaly region the Mesozoic and the Paleogene complexes are missing below the Neogene sediments, which implies uplift and erosion of Mesozoic complexes and of Paleogene sediments. It is suggested that the apical part of the anomalous body is nearest to the surface in the area of Kolárovo. The quantitative interpretation of this gravity high (Bielik 1984; Sitárová et al. 1984, 1994; Bielik et al. 1986; Šefara et al. 1987) has revealed that the density of the anomalous body varies from 2900 to 3050 kg/m³, compared to the density of the upper crust of 2700 kg/m³, the upper boundary of the anomalous body being interpreted at about 4.5–5.0 km. The depth of the center of mass of the body was interpreted at about 9.5–12.5 km. The geophysically indicated higher density mafic body below the Kolárovo gravity high has not been verified by drilling yet. Seismics also has not so far verified what this body is composed of.

Sitarová et al. (1984) interpreted the Kolárovo anomaly using stripped gravity anomalies, where the gravitational effect of Tertiary sediments was removed from the Bouguer anomaly. They interpreted a source body by means of two methods: multipole analysis and integral characteristics. They determined the source body as a right-rectangular homogenous prism of a 280 kg/m³ density contrast with a top plane at 4.5 to 5 km with a center of mass at 9.5 to 12.5 km. Bielik et al. (1986) interpreted the Kolárovo high Bouguer anomaly stripped of the gravitational effect of the sediments by means of 3D forward modeling using polyhedra. The determined source body (ibid) of a 300 kg/m³ density contrast descends steeply from its apical part at depth 4.5 to 5 km to depths of 10 to 12 km, and then gently down to some 20 km. Sitarová et al. (1994) interpreted the Kolárovo high using stripped gravity anomalies by means of the so-called “option method” that utilizes automated minimization of a multiparametric functional approximating the source body by vertical steps. In this method source masses can concentrate and grow. Their solution consists of a set of blocks (ibid). The upper boundary of their source body ascends to depths of 5 to 6 km (still below the basement of the Tertiary sediment basin fill) while its bottom boundary is at 13 km. A novice inversion method of Pohánka (2001), called the “harmonic inversion” yields a new interpretation in terms of the anomalous body generating the Kolárovo high, the center of mass of which appears to be at 10 km or even lower. The Truncation Filtering Methodology interpretation of the Kolárovo high yielded an estimate of the depth of the center of mass of the body at 8.7 km (Vajda et al. 2002).

The Kolárovo magnetic high (N4 anomaly in Kubeš et al. 2010) coincides with the Kolárovo gravity high (Fig. 1). Bezák et al. (1997) interpret the magnetic anomaly as caused by basic crystalline complex rocks or mafic remnants from a suture of the Meliatic ocean due to emplacement of asthenolith associated with extension processes in the Neogene.

Other anomalies in the vicinity of Kolárovo were also interpreted in this manner. Valach & Váczyová (1999) interpret their ground-measured magnetic profile across the anomaly by means of a damped approximate modeling technique (for potential field data inversion) in terms of a 2D basaltic intrusion of a polygonal shape rising from a basalt stratum. Their body has its lower boundary at 18 km while its top boundary rises to depths of 5.3–6.6 km depending on the number of vertices of the modeled polygonal body. Kubeš et al. (2010) interpret the Kolárovo magnetic anomaly (N4 of their map based on aeromagnetic data) by means of modeling (using the Oasis Montaj geophysical software) in terms of a basic intrusive body with its top interface at depths of 5.5 to 6 km (ibid), and so still within the bedrocks of the Tertiary sediments.

Data

The gravity data set, given in an equidistant regular grid, was obtained from Pohánka (2001), who preprocessed the gravity data of (Kubeš et al. 2001). The origin of the local planar coordinate system chosen for our gravity study area lies at the point of latitude 47°57' N, longitude 18°00' E, and height above sea level of 110 m, the x-coordinate being easting and y-coordinate northing. The gravity data are represented by the vertical component of the gravitation acceleration vector. Since the given area lies in lowlands and is relatively flat (variations in height are of only a few meters), no topographic correction was applied, while the data were vertically reduced to the reference altitude of 110 m using the free air gradient. The regular equally spaced grid of data was produced from the original irregularly placed data points by an in-house interpolation method described by Pohánka (2001). The interpolation method smoothes the data according to a given parameter, the so-called smoothing distance. Gravity data were interpolated onto a 200 by 200 meter grid. A smoothing distance of 400 m was chosen, while the mean minimum distance between the original data points was 425 m, which resulted in minimum smoothing effect. A mean value over the regular grid was subtracted from the gridded gravity, resulting in a local gravity anomaly relative to the surrounding regional field. The gravity data are shown in Fig. 1c.

A magnetic profile data set was made available to us by Fridrich Valach (Valach & Váczyová 1999). This profile of total magnetic field measurements, striking at 15° north-west, crosses borehole K288 (latitude 47°57' 01" N and longitude 18°02' 09" E) at its 18th km. The profile magnetic data are shown in Fig. 9. Aerial magnetic data for the Kolárovo area were taken from Kubeš et al. (2001) on a selected rectangle specifying our study area (Fig. 1d). The towns of Kolárovo and Nesvady are displayed in Fig. 1 for geographical orientation.

Inversion method

The inversion method used in our study is the so-called “method of local corrections” that has been developed by Prutkin (1983, 1986). It has been applied in global studies

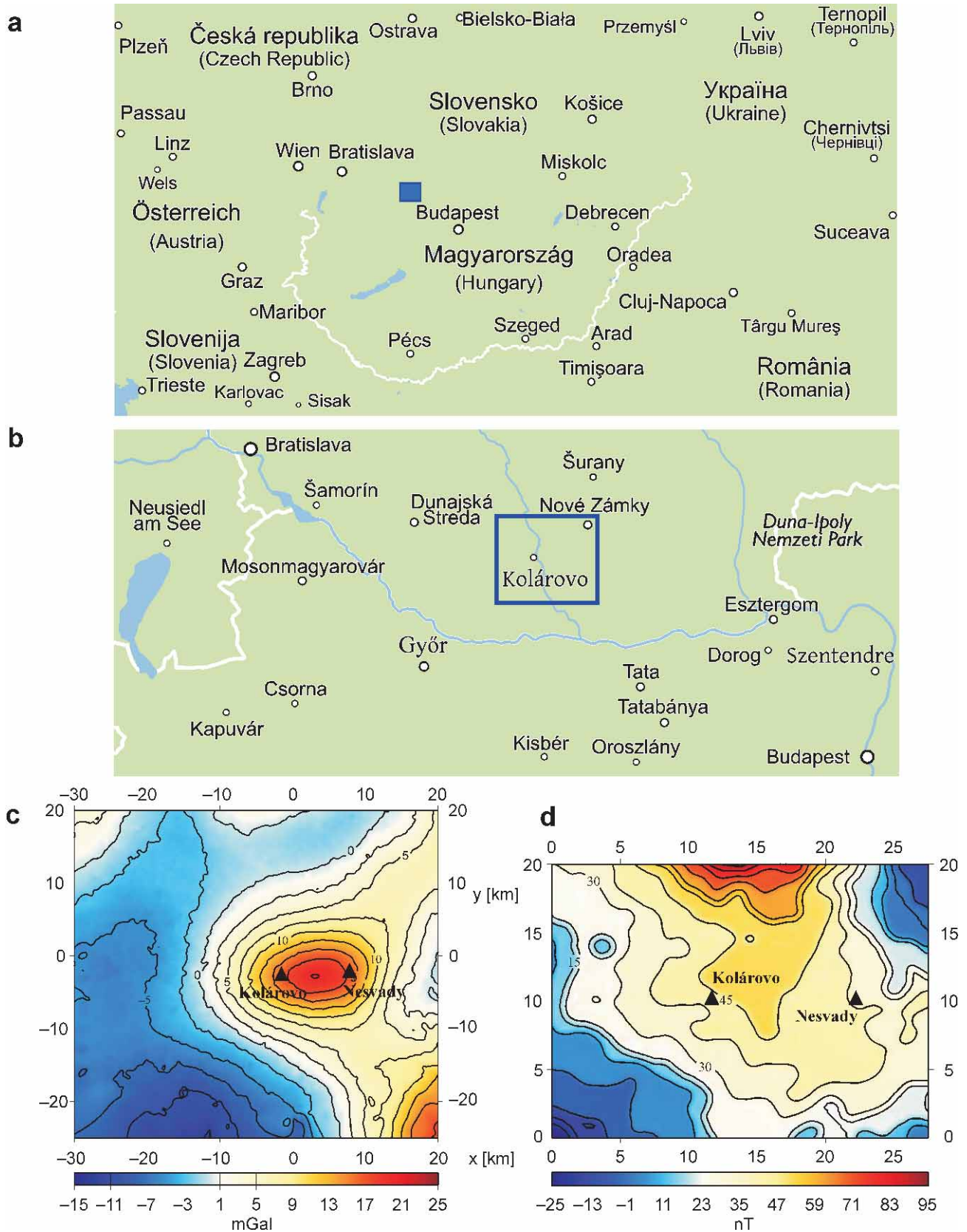


Fig. 1. **a** — Location of the study area (rectangle) within the Carpatho-Pannonian Region; **b** — Location of the study area (rectangle) within the Danube Basin of southern Slovakia; **c** — Observed gravity data (mGal). Horizontal coordinates are local easting (x) and northing (y) both in [km], specifically chosen for the gravity dataset; **d** — Observed magnetic data (nT). Horizontal coordinates are local easting (x) and northing (y) both in [km], specifically chosen for the magnetic dataset.

when inverting gravity or magnetic data in terms of major interface surfaces in planetary bodies (Prutkin 1989, 2008). In regional studies it has been applied to invert gravity and magnetic data in order to determine the Moho boundary in the Red Sea area (Prutkin & Saleh 2009). The capabilities of the method for interpreting gravity data in local/regional structural studies were demonstrated also on the Kolárovo gravity high (Prutkin et al. 2011). Here we attempt a joint interpretation of both the magnetic and gravity data in the area of the Kolárovo anomaly taking into consideration previously published interpretations, as well as tectono-geological evidence.

This inversion method for potential data consists of two main steps. In the first step the data are pre-processed so as to extract (separate) the signal contained in the data that originates from sources in a preselected depth interval. This is achieved by subsequent harmonic upward and downward continuations of the data in the region. The second step represents the 3D inversion. This step depends on whether a contrast contact surface or an anomalous source body is sought. In the case of solving for sources represented by anomalous compact bodies, first the 3D position and approximate shape of the sources is estimated using 3D line segments approximation. Next a non-linear inverse problem is solved in terms of integral equations, seeking the geometry of the surfaces of arbitrary compact convex anomalous bodies. In doing so, the line segments approximation is necessary to initiate the inversion procedure and to arrive at a solution. In the case of solving for sources represented by contrasting contact surfaces, the non-linear inverse problem, given also in terms of integral equations, is solved without the need for line segments approximation, seeking the geometry of the contrast contact surfaces. In both cases — bodies and contact surfaces — no linearization is applied to solve the inverse problem. Instead, a method of local corrections is adopted. All the procedures of the inversion method, to be applied here, are described mathematically in detail by Prutkin et al.

(2011). Below we describe them only phenomenologically, to make the manuscript transparent and briefer.

Depth-wise signal separation of sources

The purpose of the depth-wise signal separation is to isolate the signal of multiple vertically distributed sources. In the case of the Kolárovo anomalies, the source (causative) body/bodies are assumed to be in the crystalline basement beneath the Neogene sediments. The thickness of the sediments in the lowland varies between 2.3 and 3.7 km in the Kolárovo area. We chose to eliminate the signal of sources between the topographic surface and the depth $d=2$ km. Later we also separate the signal into that of a lower crust elevation and that of an intrusion above it, by preselecting a depth d of the division level. The separation is accomplished by making the observed field harmonic down to the depth d . Our numerical procedure is based on subsequent triple harmonic continuations: upward over d , downward over $2d$, and upward again over d .

First we continue the observed data upwards from the topographic surface to the height $h=d$ to attenuate the effect (signal) of the sources in the near-surface layer. This numerical procedure causes major errors in the vicinity of the geographical boundary of the study (survey) area. To reduce these truncation errors and edge effects we need a model of the regional field to be subtracted from the observed field prior to the upward continuation. The regional field is determined mathematically as a harmonic function (in 2D sense) within the study area matching the observed data on the boundary of the study area. The gravity and magnetic regional fields determined by this method are shown in Fig. 2. When we subtract the regional field, the residual field will be equal to zero at the geographical boundary of the area. By harmonically continuing the data with such a trend removed, no truncation errors are introduced by numerical integration (evaluation of the Poisson integral of the upward continuation in planar approxi-

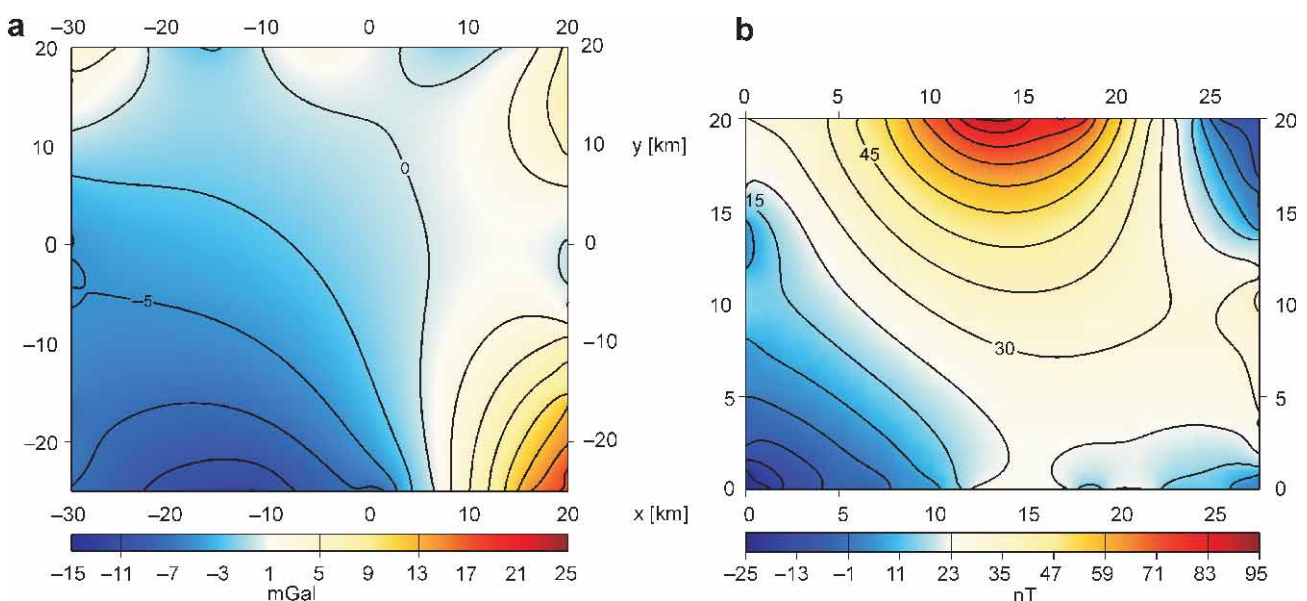


Fig. 2. **a** — Regional gravity trend (mGal); **b** — Regional magnetic trend (nT).

mation) over the residual field. Due to properties of harmonic functions, the regional trend (field) has no extremes (minima or maxima) within the study area, so we do not create false anomalies (and respective false causative bodies).

Second, we continue the obtained function downwards to the depth d below the earth's surface, which means vertically over the distance $2d$. While the upward continuation represents a direct problem solved by numerical evaluation of the surface Poisson integral, the downward continuation represents an inverse problem formulated by an integral equation (the Poisson integral). As it is a linear ill-posed inverse prob-

lem, some regularization must be, and is, applied (cf. also Paštka et al. 2012).

Third, the field is harmonically continued upward from depth d back to the surface. This three-step continuation procedure (Vasin et al. 1996) produces a field that is harmonic everywhere above depth d . Consequently the resulting field represents a signal of causative bodies (sources) from below the depth d . The detailed description of this procedure including the mathematical apparatus is given in section 2 of (Prutkin et al. 2011). We apply the above described procedure to the Kolárovo gravity anomaly. Our goal is to remove the signal of shallow sources down to the depth of 2 km, which corresponds to a safe minimum thickness of the Neogene sediments. In Fig. 3 we present the Kolárovo gravity anomaly after removal of the signal of shallow sources with the regional trend restored. The amplitude and pattern are practically unchanged (compare with Fig. 1a). The obtained field is very similar to the original one. It is a confirmation that the Kolárovo gravity high is caused mainly by deeper sources.

The Kolárovo magnetic anomaly after removing the regional field (trend) and after removing the signal of shallow sources down to the depth of 2.5 km, namely the residual magnetic field, is shown in Fig. 10.

Line segments approximation of sources

Next the sources are approximated by 3D line segments that approximately generate the residual field (data) obtained by removing the regional trend and the signal of shallow sources. The line segments indicate the location and geometry of the causative bodies (sources), as well as their relative strengths or relative contributions to the residual field. Each line segment is defined by 7 parameters: 3 for the position of each end point, and 1 for its density/magnetization. The parameters are resolved from the residual field data by means of non-linear minimization (Prutkin et al. 2011).

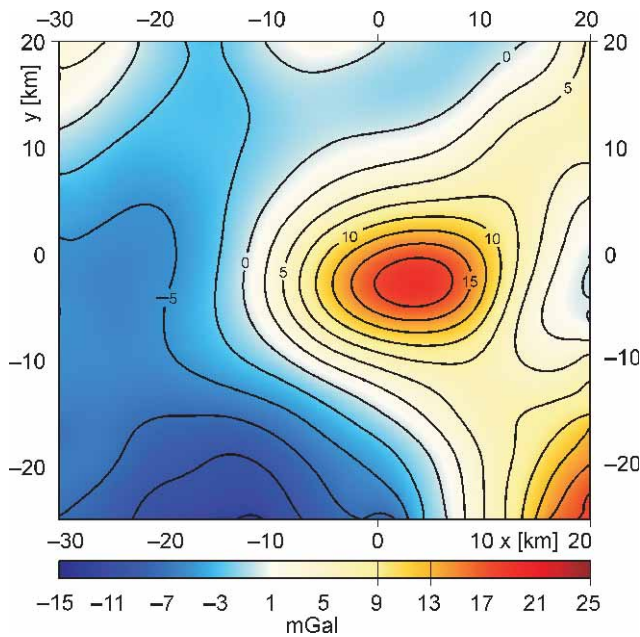


Fig. 3. Observed gravity data after removal of signal of shallow sources down to the depth of 2 km (mGal).

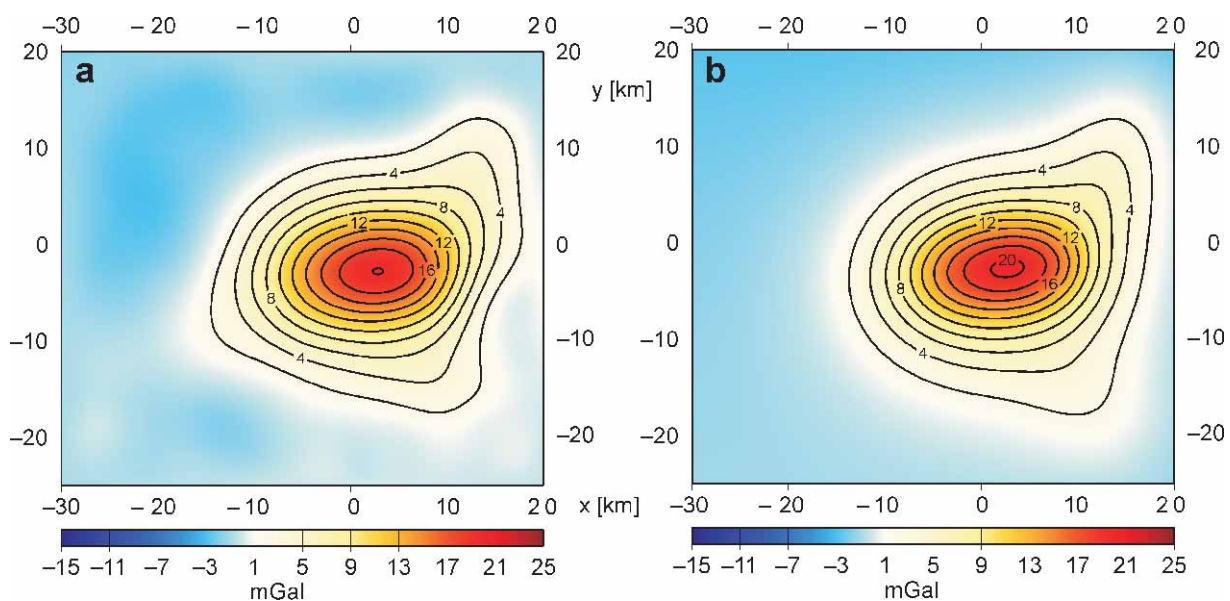


Fig. 4. **a** — Residual gravity anomaly (mGal); **b** — Gravity field of 3 line segments (mGal).

Three line segments are sufficient for fairly accurate approximation of the Kolárovo gravity data. The RMS of differences between the residual gravity data and the field of the line segments is 0.57 mGal. The residual gravity field (a) and the field of the three line segments (b) are presented in Fig. 4. All three line segments lie at depths between 6 and 9 km. It should be noted that we were seeking 21 parameters of the line segments respective to nearly 60,000 observations. Hence, this procedure is quite stable.

Inversion by the method of local corrections

Next the residual field is inverted. The inversion is carried out for restricted classes of causative bodies. When we seek the geometry (shape) of an unknown homogenous body; the only requirement is that the sought body is assumed to be star-convex relative to some point of the body. The position of this point is chosen with the help of the 3D line segment approximation. The boundary of the body is described by a radius vector from this point, the radial distance being a function of two angles of the local spherical coordinate system centered at this point. The body is assumed to be homogenous and of a preselected density contrast. The gravitational inverse problem can be reduced to a non-linear integral equation respective to an unknown function — the 3D geometry of the boundary (Prutkin et al. 2011). For this restricted class of solutions and for a fixed preselected value of the density contrast, the solution of the inverse problem is unique. This inverse problem is solved by the so-called “method of local corrections”. The integral equation for the boundary is upon discretization turned into a system of non-linear equations that are solved in an iterative fashion. Again, the problem is ill-posed and requires regularization. The method is described in detail including the mathematical apparatus in (Prutkin et al. 2011). The method of local corrections can also be used for another class of restricted solutions — for a contact surface of a density contrast (density interface). In this case the line segments approximation is not required. The density contrast and the vertical position — depth D of the horizontal asymptotic plane — are pre-specified. The mathematical apparatus for this inversion procedure is described in detail in (Prutkin & Saleh 2009). The solution of our non-linear inversion can also consist of a combination of anomalous bodies and contact surfaces.

Inversion results

In this section we will present several solutions that can be reached by the inversion method based on the method of local corrections. In the case of the Kolárovo gravity anomaly, we found three line segments representing the sources. The central line segment has a substantially higher line density than the other two. In “solution A” we relate the field of the two lighter segments to the bedrock topography (bottom boundary of sediments) that we determine — using the method of local corrections — as a contact surface. We attribute the effect of the main (central) line segment to an anomalous body representing an assumed mafic intrusion.

For this body we assume a density contrast of 300 kg/m^3 . The intrusive body found in this way is located entirely below the upper boundary of the crystalline basement (Fig. 5). The depths to the basement obtained by inversion vary between 2 and 3 km (Fig. 5). Figure 5a shows a plan view of the mafic intrusion (including its respective line segment), as well as the basement topography presented by means of depth isolines. Figure 5b and 5c show W-E and S-N cross-sections of “solution A”, respectively. In the vertical sec-

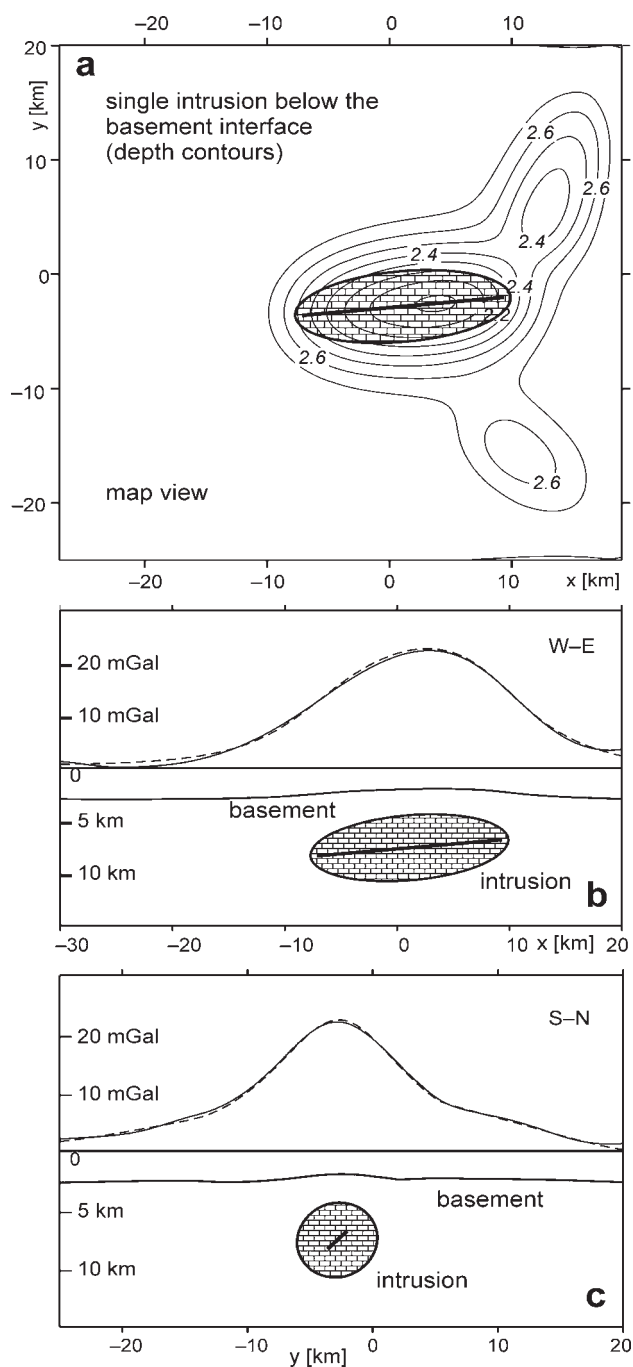
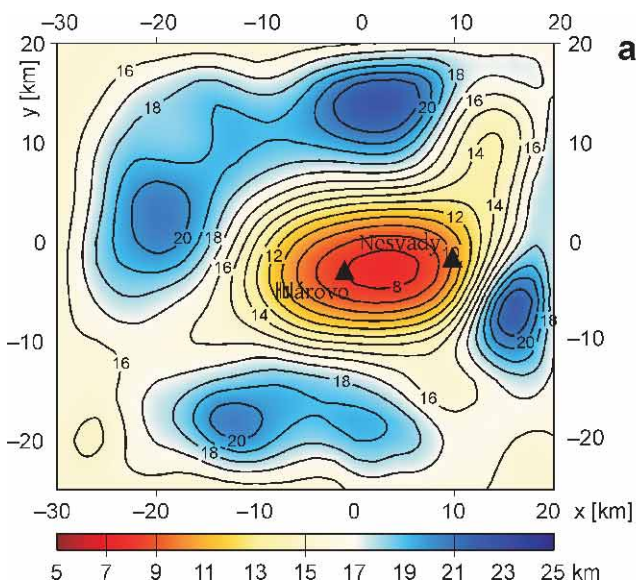


Fig. 5. a — Solution A, plan view. Depth isolines [km] define the shape of the basement interface; b — Solution A, W-E vertical section; c — Solution A, S-N vertical section.

tions the solid line above the surface corresponds to residual gravity and the dashed line to the gravity generated by the obtained sources of “solution A”. Depths to the center of mass of the intrusion, as well as to the upper and lower boundary of the body, are in good agreement with the previous interpretations of Sitárová et al. (1984, 1994) and with the upper part of the anomalous body of Bielik et al. (1986).

By means of our methodology we can obtain an alternative solution, denoted as “solution B”, that is also admissible from the viewpoint of gravity data. We can attribute all gravity signal to an elevation of a contact surface of a density contrast of 300 kg/m^3 , representing the density interface between felsic crystalline crust and mafic lower crust. In this case, we do not need the approximation by 3D line segments. We directly invert the residual gravity data. The method of local corrections provides depths to the contact surface. They vary from 22.5 km at the outskirts of the study area to 7.5 km respective to the peak of the gravity high. Solution B is presented in Fig. 6 in two ways: (a) as a map of the contact surface topography (depth isolines), and (b) as a shaded 3D surface. For visualization of 3D objects we use the Poisson Surface Reconstruction software (Kazhdan et al. 2006).



Another admissible solution, denoted as “solution C” is shown in Fig. 7. Therein, we attribute the whole residual gravity signal (Fig. 4a), approximated by the field of the three line segments (Fig. 4b), to a single causative body representing a mafic (basic) intrusion. In this case, we obtain an intrusive body similar to that of “solution A”, presented in Fig. 5, but with a more complex geometry. Figure 7b shows its W-E cross-section running through the center of the gravity high at $y = -2.5 \text{ km}$.

Yet another admissible solution, denoted as “solution D” (Fig. 8), is based on the following considerations. By the triple harmonic continuation procedure (of sec. 3.1) we have removed from the observed gravity data the signal of sources between the surface and the preselected depth of 10 km. The remaining gravity signal has an amplitude of 10 mGal (roughly a half of the original amplitude). This is a clear indication that a part of the source of the Kolárovo gravity high may lie below the level of 10 km. The gravity signal of the deeper source looks like a low-frequency isometric anomaly. We relate this signal to an elevation of mafic lower crust (density contrast of 300 kg/m^3 relative to the felsic crust). After subtracting this low-frequency signal, we re-

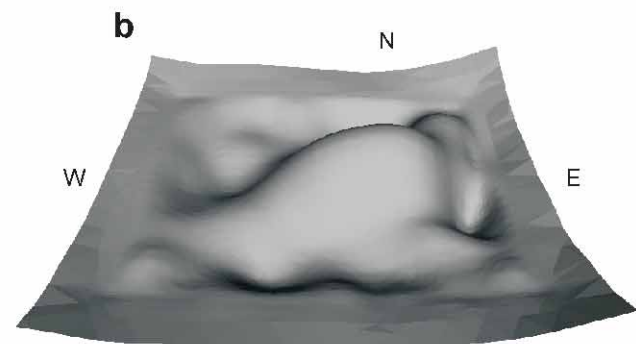


Fig. 6. a — Solution B: Upper/lower crust interface (depth isolines [km]); b — Solution B: Upper/lower crust interface (3D shaded view).

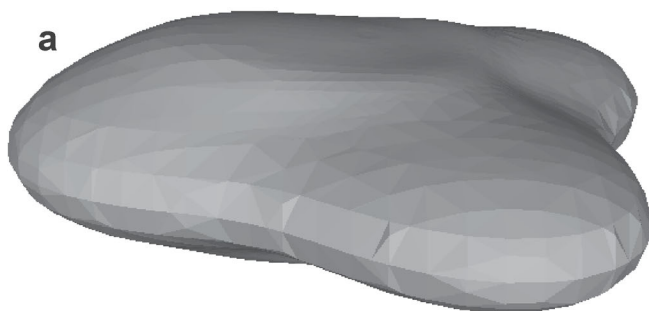
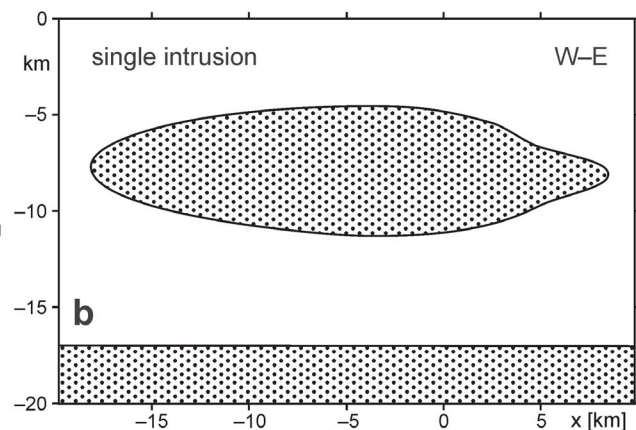


Fig. 7. a — Mafic intrusion of solution C (3D shaded view); b — W-E vertical section of solution C.



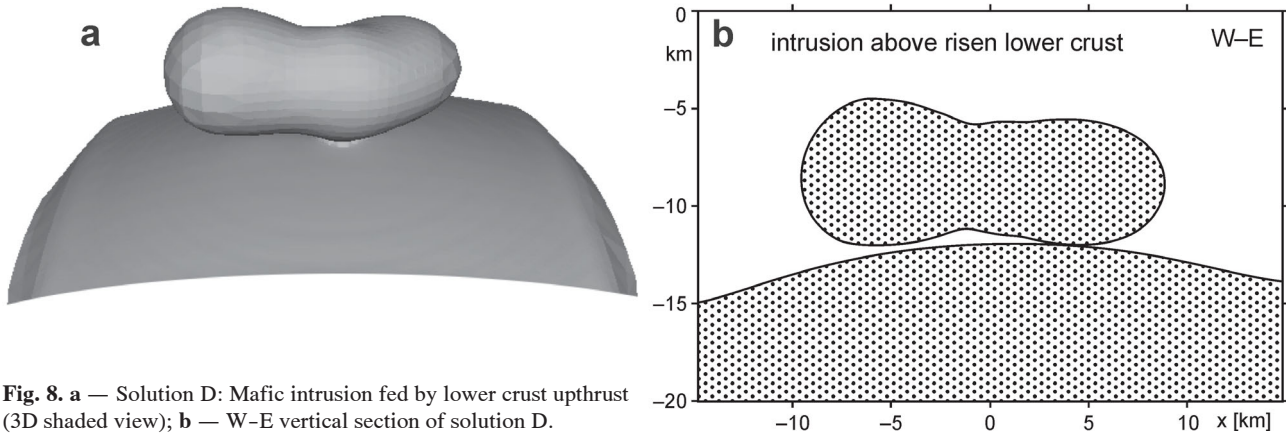


Fig. 8. a — Solution D: Mafic intrusion fed by lower crust upthrust (3D shaded view); b — W-E vertical section of solution D.

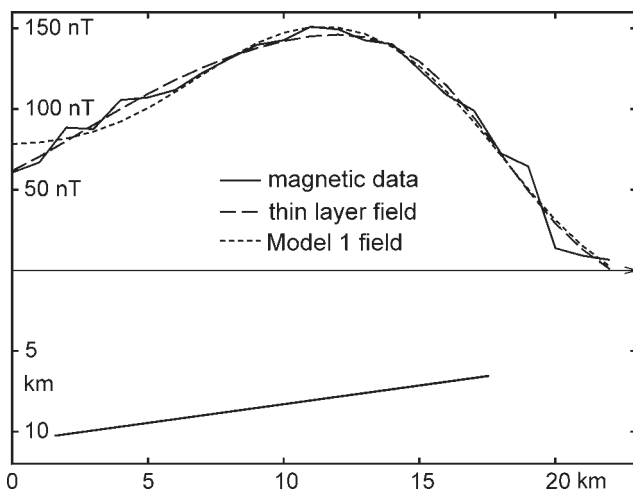


Fig. 9. Inversion results for Kolárovo magnetic profile data.

ceive a remaining field. This remaining field can be approximated quite accurately (on the level of 0.75 mGal) by two 3D line segments. By the method of local corrections a compact anomalous body respective to these two line segments is found, which represents an intrusive mafic body. Hence “solution D” consists of the upthrust of the mafic lower crust above which is the mafic intrusion. Compared to solution C the intrusion is smaller and of different shape. Figure 8a shows solution D in 3D, while Fig. 8b its W-E vertical cross-section running through the center of the gravity high at $y = -2.5$ km.

We can see that in the case of gravity data there are several admissible solutions, within the class of restricted solutions defined in terms of density contrast contact surfaces (interfaces) and star-convex homogenous causative bodies that can satisfy the observed gravity field. These solutions may help to resolve the tectono-structural geological situation. Once a solution is selected and a density contrast specified, the geometry of a causative body or a contact surface is determined by the inversion method uniquely. All the presented gravimetric solutions were obtained by assuming a density contrast of 300 kg/m^3 , meant to represent the contrast between upper and lower crustal material. Theoretically a different density contrast could have been selected, leading to

similar gravimetric solutions of different sizes and shapes, which would expand the number of admissible solutions.

Let us now turn our attention to inverting the magnetic data in the same area. The profile of magnetic data was approximated by means of a set of thin layer magnetic anomalies. This 2D source represents a cylinder the section of which is, by any perpendicular plane, a line segment. Only one thin layer is sufficient for reasonable approximation of magnetic data (see Fig. 9). Since this source is determined by 5 parameters only (scalar magnetization and 4 coordinates of 2D line segment ends), our inversion for thin layer parameters is very stable. Results are slightly better than for the best model, “Model 1”, of Valach & Váczyová (1999). Residuals between magnetic data and thin layer anomaly have $\text{RMS} = 5.97$ nT, while the model of Valach & Váczyová (1999) has $\text{RMS} = 7.81$ nT. In the left part of the profile the approximation by the thin layer anomaly performs definitely better. The length of the line segment in Fig. 9 is probably too big, because we treat the source of the Kolárovo magnetic anomaly as a two-dimensional source. The depths to the segment ends are again between 6.5 and 10 km. This indicates that the intrusive body is magnetic in this interval of depths.

In terms of areal magnetic data at Kolárovo (Fig. 1b), we first calculate a 2D harmonic function, which represents a model regional field, namely a trend to be removed (Fig. 2b). This regional trend is assumed to represent the effect from sources beyond the area of investigation. After removing this trend we apply the triple harmonic continuation procedure to remove the signal of shallow sources down to the depth of 2.5 km. This results in a residual magnetic field (Fig. 10). Next we transform this residual magnetic field into pseudo-gravity. For this purpose we exploit a simple layer integral distributed on a surface parallel to the physical one. This procedure is described in detail mathematically in (Prutkin et al. 2012). The computed pseudo-gravity is shown in Fig. 11. Pseudo-gravity is then approximated by one, two and three line segments. They are located at depths between 5 and 10 km, just like those in the case of the Kolárovo residual gravity anomaly. This coincidence gives a strong case for the notion that both the gravity and the magnetic fields are caused by the same source, and that the source body is magnetic down to at least the depth of 10 km. Finally the method of local corrections is applied to invert the pseudo-gravity

and to obtain a magnetic model of the anomalous causative bodies in terms of a magnetic contrast contact surface (Fig. 12). Depths to the contact surface are between 7.7 and 23.5 km, which approximately matches the solution of the Kolárovo gravity anomaly in terms of a density contrast (300 kg/m^3) contact surface (solution B in Fig. 6). Depth isolines of the magnetic contact surface are presented in Fig. 12. The shape of this contact surface is similar to that obtained by gravity data inversion, but does not coincide entirely. A possible explanation is that the up-thrusted lower crustal mafic material is magnetically heterogenous, or not entirely magnetic. The Curie temperature isotherm in this area lies just above the Moho boundary (Dérerová et al. 2006; Grinč et al. 2013), so an intrusive body would start losing its magnetization only at depths approaching the Moho.

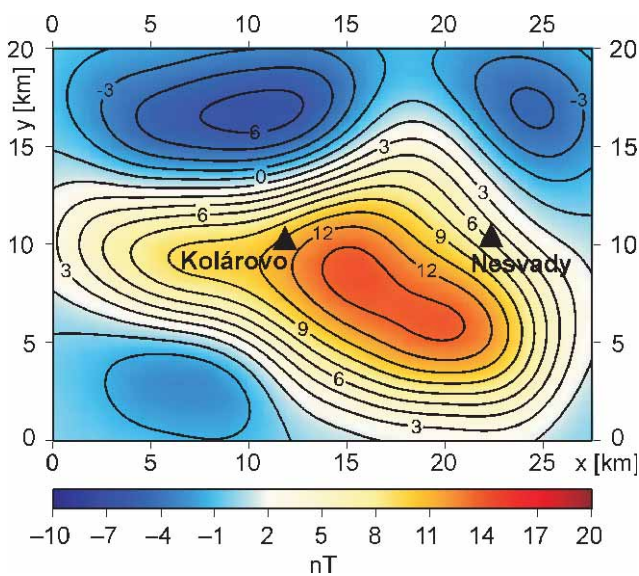


Fig. 10. Residual Kolárovo magnetic anomaly (nT).

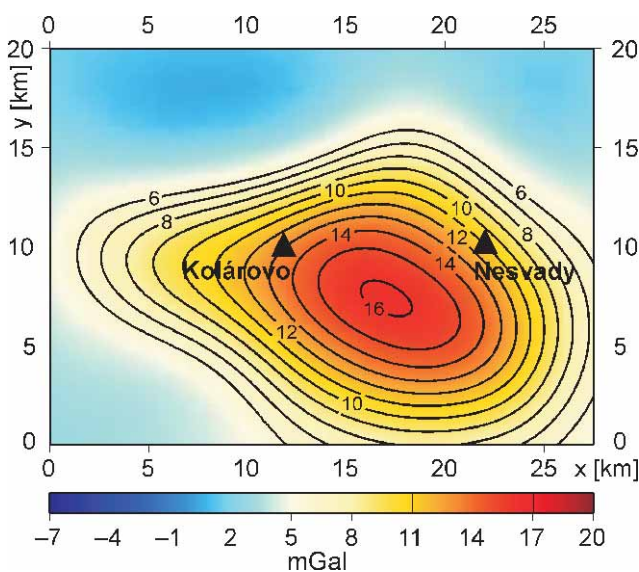


Fig. 11. Residual Kolárovo pseudogravity anomaly (mGal).

Tectono-geological interpretation of inversion results and discussion

The inversion results of gravity and magnetic data in the Kolárovo anomaly area must be viewed in the context of the tectonic evolution of the Pannonian Basin and particularly of its northern part, the Danube Basin, including the build-up of their basements. Several tectonic events and processes took part in forming the Pannonian Basin. According to current knowledge (e.g. Ratschbacher et al. 1991; Csontos et al. 1992; Horváth 1993; Kováč et al. 1993; Nemčok et al. 1998), among the most significant are: (a) escape of crustal fragments from behind the Alps into the space of the closing flysch basin already during the Paleogene and Neogene, (b) oblique collision of these fragments with the European platform, movement on strike-slip faults, (c) origination of an asthenolith due to finishing subduction, (d) thinning of crust as a result of partial melting and assimilation of lower crust, (e) subsequent extension and subsidence, sedimentation and volcanism finishing with basaltic intrusions due to differentiation of mantle material. The basin basement is very inhomogenous, formed by several crustal tectonic units (Fusán et al. 1987; Vozár et al. 2010). Tectonic borders between the segments are represented by fault zones, which mean weak zones, suitable for the rising of magmatic material or eventually mantle material. One such zone, the Hurbanovo tectonic zone, between the Veporicum tectonic unit of the Western Carpathians and the Pelso Unit of the Hungarian Midland also runs in the vicinity of the Kolárovo anomaly (Fusán et al. 1971).

When interpreting the Kolárovo anomaly there are two contrasting environments available — the upper crust (average density of 2700 kg/m^3) and the basic material (average density of 3000 kg/m^3), either in the form of an intrusion or in the form of elevated (arced up) lower crust. From the geophysical viewpoint, according to our inversion results, three scenarios are available: intrusion body, convex elevated contact surface, a combination of the two. We consider as signif-

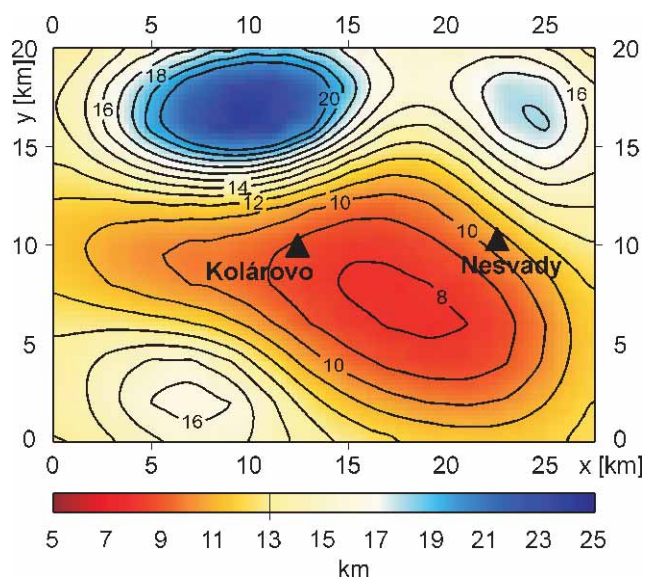


Fig. 12. Magnetic contact surface (depth isolines [km]).

icant our finding that the magnetic source body pretty well coincides with the heavier source body interpreted from gravity data, which supports a previous assumption that the source body is made up of basic material.

We comment on the individual inversion results as follows: solutions A and C — a single intrusive body of basic magma (gabbro) is acceptable with respect to its shape, but its dimensions in the context of Western Carpathians would be too rare (unique), solution B — an elevation of the upper/lower crust boundary alone would thin the upper crust in the studied region, which would also require an uplift of the Moho boundary (not considered in the inversion), solution D — a combination of an elevated lower crust surface with an intrusive body above it seems to us more likely.

According to the hypothesis/interpretation of Bezák et al. (1997) the Kolárovo anomaly is caused by mafic remnants of the Meliaticum oceanic crust inside a suture zone at which an asthenolith rose at an angle. The rise of the modified lower crust material or asthenosphere material was facilitated by an extension process that gave rise to the Danube Basin. However, our inversion results do not indicate an asthenolith or mafic remnants in a slanted position under an angle as is indicated by Bezák et al. (1997). To us a more likely explanation seems to be that the suture only served as path of least resistance for the rising magma, while the intrusion which originated shows no slanted shape. Another admissible solution consistent with both the gravity and magnetic data is a combi-

nation of an elevation of the upper/lower crust boundary and a mafic intrusion into the felsic upper crust above it, the geometry of which is given in Fig. 8. It is also possible to invert the magnetic and gravity data in terms of an isolated contrasting heavy compact anomalous body, as shown in Figs. 5, 7 and 9. However, from the viewpoint of geology and tectonic development, it makes more sense to assume a support for this body, or source of partially melted intruding upper mantle material for it, from well below the 10 or 12 km depths.

Associated with interpreting the Kolárovo anomaly is also the broader tectonic context. It is curious that this anomaly falls into a line of other magnetic and partially also gravity anomalies located within a band of NE strike along the Rába Fault, starting in Austrian territory, passing through Hungary, reaching the Hurbanovo Fault, and continuing in Slovakia in a W-E direction connecting to the Diósjenő (or Rapovce) fault system. These fault systems divide the Alpine–West-Carpathian tectonic systems from the Pelso Unit to the south, accompanied by gravity and magnetic anomalies (Bielik et al. 2006; Wybraniec et al. 2006). There is a difference between them, however. While the SW branch around the Rába Fault might have remnants of the oceanic South-Penninic crust incorporated within it, the Hurbanovo branch of the anomalies with its continuation to the NE is most likely caused by basic intrusions into the crust, which during the extension made use of the weakened part of the crust on the transported suture, only this time not of the Southern Peninic, but instead of the

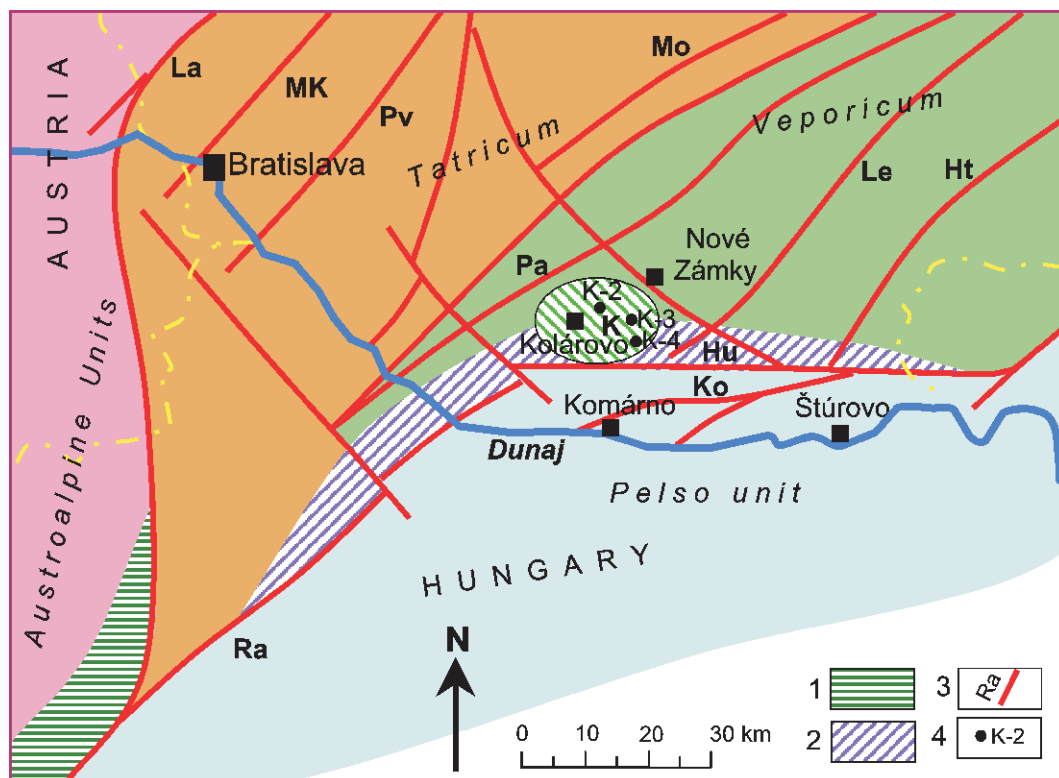


Fig. 13. The Kolárovo anomaly in its tectonic context: **1** — assumed relics of South Penninic oceanic crust; **2** — supposed relics of Meliatic oceanic crust; **3** — faults (after Tectonic Map of the Slovak Republic, Bezák et al. 2004): La — Láb, MK — Malé Karpaty, Pv — Považie, Mo — Mojmirovce, Pa — Palárikovo, Le — Levice, Ht — Hont, Hu — Hurbanovo, Ko — Komárno, Ra — Rába; **4** — Kolárovo boreholes: K — Kolárovo anomaly.

Meliaticum. The South-Penninic suture must have occupied a forefield of the Tatricum and Veporicum complexes, into which it also extends, or wedges, while the Meliaticum suture was located more to the south, on the border with the Pelso Unit (being composed by Paleozoic rocks as the equivalent of the Graz Paleozoicum of the Upper Austro Alpine Units and blocks of the Cadomian basement). The Penninic suture was transported during the Neogene movements of the Inner West-Carpathian blocks towards the NE, and therefore its remnants, if they exist, can be located below the Tatricum. Additional blocks of Pelso type, pulled up from SW, apparently dragged with them in the forefield remnants of the oceanic Jurassic suture zone of the Meliaticum. The position of the Kolárovo anomaly has already been defined similarly (Bezák et al. 1997). Šefara & Szabó (1997) prefer an explanation involving an intrusion of upper mantle material of a laccolith type, but they link it with the Rába-Hurbanovo system. For reasons stated above these two tectonic systems should be distinguished as distinct. That is why the interpretation of Balla (1994) regarding a possible continuation of the south-Penninic structure into the Hurbanovo fault is unlikely. Moreover, the anomalous bodies such as those in the Ivrea zone have different density and geometric characteristics. From a tectonic point of view the occurrence of eclogitic bodies in the upper crust is possible, however, it leads to the same issue, that such bodies (e.g. Janák et al. 2004) are of a different shape and size than the Kolárovo body.

The position of the Kolárovo anomaly in relation to tectonic structures is illustrated in Fig. 13. There the position of the main tectonic units (Austro-Alpine units, Tatricum, Veporicum, Pelso), of the assumed suture zones of the South-Penninic and Meliaticum, as well as of the individual faults according to the Tectonic Map of the Slovak Republic in the scale 1:500,000 (Bezák et al. 2004) is shown.

Conclusions

The inversion methodology presented here represents a versatile approach to interpreting potential field data in tectono-geological studies. Its flexibility dwells in separation of multiple source signals. Its merit is in producing several admissible solutions that can be — from the viewpoint of geological or tectonic interpretation — studied, compared and evaluated in terms of their feasibility in the context of the tectono-geological situation and evolution in the studied area. This versatility of the applied inversion methodology is demonstrated here by producing several admissible gravimetric inversion solutions for the Kolárovo anomaly:

- 1) A simple intrusive body below the basin sediments at the depth interval between 5 and 10 km, while determining also the shape of the bedrock boundary, obtained by dividing the gravity signal into a contribution of the intrusion and a contribution of the sediments/bedrock interface (solution A);
- 2) A more complex single intrusive body at the depth interval between 5 and 11 km, obtained by assigning all the gravity signal to the intrusion (solution C);
- 3) An upper/lower crust contact surface defined by its 3D shape, obtained by attributing the entire gravity signal to an

elevation of this discontinuity (density contrast) surface (solution B), reaching the altitude of slightly above 8 km below sea level (b.s.l.);

4) A rise of the upper crust (upwards to the level of 12 km b.s.l.) feeding an intrusive body above it (at an interval of depths between 5 and 12 km), representing upthrusting of basic magma into the upper crust, obtained by distributing the gravity signal to the intrusion and to the lower crust uplift (solution D).

All the listed solutions were obtained by assuming a density contrast of 300 kg/m^3 , meant to represent the contrast between upper and lower crustal material.

All the presented gravimetric solutions equally well match the observed gravity anomaly. They cannot be discriminated based on observed surface potential field data. The discrimination among these solutions must be carried out on the basis of additional geophysical or earth science constraining information and tectonic and geological considerations. In the light of the tectonic evolution of the Carpatho-Pannonian area we consider solution D as the most realistic, though not unique. The joint interpretation of magnetic and gravity data in the area of the Kolárovo anomaly has confirmed that the higher density basic intrusive body is to a great extent also magnetic.

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