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High resolution Slovak Bouguer gravity anomaly map and its enhanced derivative transformations: new possibilities for interpretation of anomalous gravity fields

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Abstract: The paper deals with the revision and enrichment of the present gravimetric database of the Slovak Republic. The output of this process is a new version of the complete Bouguer anomaly (*CBA*) field on our territory. Thanks to the taking into account of more accurate terrain corrections, this field has significantly higher quality and higher resolution capabilities. The excellent features of this map will allow us to re-evaluate and improve the qualitative interpretation of the gravity field when researching the structural and tectonic geology of the Western Carpathian lithosphere. In the contribution we also analyse the field of the new *CBA* based on the properties of various transformed fields – in particular the horizontal gradient, which by its local maximums defines important density boundaries in the lateral direction. All original and new transformed maps make a significant contribution to improving the geological interpretation of the *CBA* field. Except for the horizontal gradient field, we are also interested in a new special transformation of *TDXAS*, which excellently separates various detected anomalies of gravity field and improves their lateral delimitation.

Key words: complete Bouguer anomaly, horizontal gradient, regularized derivatives, Western Carpathians

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1. Introduction

The outputs from qualitative (transformed fields) and quantitative (density modelling) gravimetric interpretation are very important for the study of the structure and tectonics of the Western Carpathian lithosphere. The regional gravimetric database on the territory of the Slovak Republic represents very valuable material, which is the basis for calculating the complete Bouguer anomaly (*CBA*) field.

The gravimetric measurements with a scale of 1:25000 have been realized since 1956 and were finished in 1992. The resolution and accuracy of the gravity data depended on the type of gravimeters, processing methods and roughness of topography (*Bielik et al., 2006*). Revision of this gravimetric database was carried out between 1998 and 2001 (*Grand et al., 2001*). The revision mainly corrected some systematic errors in the calculation of terrain corrections. This database included about 230000 stations.

The current gravimetric database has been upgraded and enriched and it currently contains 319,915 points (*Zahorec et al., 2017b*). One of the most important steps in calculating the new version of the *CBA* field was to calculate the terrain correction values using a more detailed and accurate digital terrain model (DMR-3; *TOPÚ, 2012*). In addition, atmospheric corrections have been recalculated (considering the influence of the terrain) and some global impacts have been estimated (e.g., influence of distant topography beyond a radius of 166.7 km). The resultant *CBA* field represents very important material for the interpretation of the structure, composition and tectonics of the Western Carpathians in our territory. The calculation of higher derivatives of *CBA* field and their transformed fields improves significantly the resolution of the original *CBA* field, especially for detecting and tracing of the density contacts in the horizontal direction, as it can be seen in the presented case studies.

2. Methodology of complete Bouguer anomaly field determination

The values of *CBA* were calculated based on the given formula (Eq. 1), with standard procedures being used in most correction terms (*Zahorec et al.,* *2017b*). For the calculation of atmospheric correction values, an approach was applied, which takes into account the lower boundary of the atmosphere represented by the topography. So, the formula used for *CBA* evaluation has the form:

$$CBA(P) = g(P) - \gamma(P_0) - \delta g_F(P) - \delta g_{sph}(P) + TC(P) + \delta g_{atm}(P) \;\; [\text{mGal}], \quad (1)$$

where: $g(P)$ is the gravitational acceleration at the point of the database, converted to the 1995 gravity system; $\gamma(P_0)$ is the normal gravity field (the so-called formula "Pizetti-Somigliana" for the parameters of the reference system GRS80, *Moritz, 1984*); $\delta g_F(P)$ is the "free-air" correction in the approximation of second degree (*Wenzel, 1985*); $\delta g_{sph}(P)$ is the gravitational effect of the truncated spherical layer (*Mikuška et al., 2006*) with a half apex angle $1°29'58''$ (corresponding to the distance approximately 166.7 km); $TC(P)$ are terrain corrections for zones of $T1$ (0 − 250 m), $T2$ (250 m − 5.24 km), $T31$ (5.24 km − 28.8 km) and $T32$ (28.8 km − 166.7 km) and were calculated by program Toposk (*Marušiak et al., 2013; Zahorec et al., 2017a*). The effects of topographic and bathymetric masses beyond the 166.7 km range were determined by approach of *Mikuška et al. (2006)*, but have not been finally included in the resultant presented field due to their small value range; $\delta g_{atm}(P)$ is atmospheric correction for atmospheric masses bounded from below by topography (*Mikuška et al., 2008*).

In Equation 1 we denote by the symbol P the position of the measuring point and with P_0 its measurement projection to the level of the reference ellipsoid. When calculating the new version of the *CBA* we did not consider so-called an indirect geophysical effect (*Vajda and Pánisová, 2007*). The *CBA* fields were calculated for the different correction density values (entered into the $\delta g_{sph}(P)$ and TC terms in Equation 1): 2.00, 2.20, 2.45, 2.55, 2.67 and 2.75 g·cm^{-3}, for regional studies we use the standard value of 2.67 g·cm^{-3} (Fig. 1).

3. Calculations of transformed fields from complete Bouguer anomaly

Various visualization techniques, using illuminated surfaces with different colour scales (Fig. 1), or transformed fields using numerically calculated

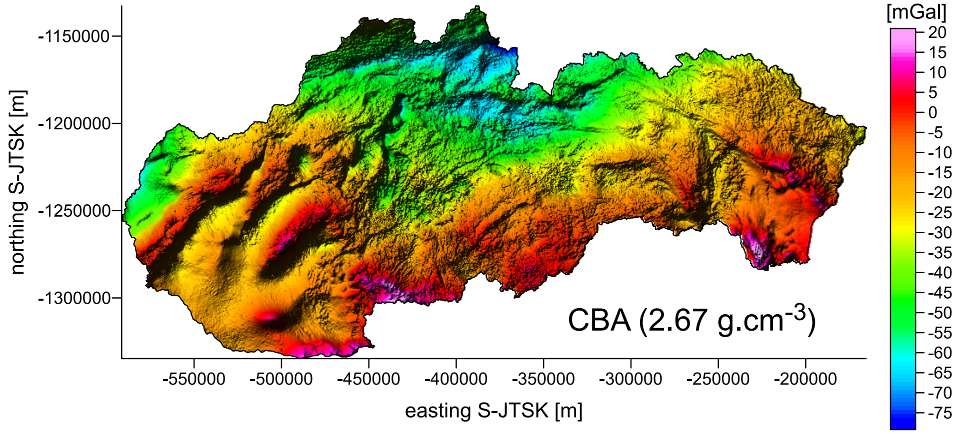

Fig. 1. Map of the new version of the *CBA* field for the Slovak territory (for correction density of 2.67 g·cm^{-3}).

higher derivatives of anomalous field ($\partial f/\partial x$, $\partial f/\partial y$, $\partial f/\partial z$), and their relative ratios, help in the qualitative interpretation of fields of complete Bouguer anomalies. The most famous are the following transformations:

– horizontal gradient: $HG = \sqrt{(\partial f/\partial x)^2 + (\partial f/\partial y)^2}$,
– analytical signal: $AS = \sqrt{(\partial f/\partial x)^2 + (\partial f/\partial y)^2 + (\partial f/\partial z)^2}$, (*Nabighian, 1972, 1984*),
– tilt derivative: $\text{tilt} = \text{arctg}\dfrac{\partial f/\partial z}{HG}$, (*Miller and Singh, 1994; Verduzco et al., 2004*),
– theta derivative: $\cos(\theta) = \dfrac{HG}{AS}$, (*Wijns et al., 2005*),
– *TDX* derivative: $TDX = \text{arctg}\dfrac{HG}{\partial f/\partial z}$, (*Cooper and Cowan, 2006*),
– *TDXAS* transformation: $TDXAS = TDX \cdot AS$, (*Stampolidis and Tsokas, 2012*).

Even though each of these transformations reacts in other ways to the presence of density boundaries in the basement, two important cases can be identified: a) the transformed field reacts with a steeper gradient compared to the original interpreted field of the *CBA* and b) the transformed field reaches maximum values over a vertical or sub-vertical density boundary, which is better interpretable. These properties are demonstrated on the synthetic model (Fig. 2), where we illustrate the transformed field curves above the rectangular step model at a depth of 200 m below the surface and with density contrast of 0.4 g·cm^{-3}. The anomalous fields V_z and V_{zz} (the first vertical derivative of anomalous gravitational acceleration) show a typical gradient of the field with the inflection point above the edge of the step (Figs. 2a,b), the horizontal gradient field (*HG*) and the analytical signal (AS, as well as the total gradient) clearly define the position of contact based on their maximum value (Figs. 2c,d). Transformations based on derivative relations – the so-called "tilt"-derivative and *TDX*-derivative, point to the presence of a contact on the basis of their significant gradient (Fig. 2e, g), which is in the case of the transformation of the *TDX* much more expressive. The special transformation *TDXAS* (*Stampolidis and Tsokas, 2012*), which should be seen rather as a mathematical filter (multiplication of fields *AS* and *TDX*) is very interesting. We find the physical reality of this transformation very difficult. Nevertheless, it gives very interesting results and its significant gradient clearly indicates the contact boundary.

We have applied the given transformations to the grid of anomalous field *CBA* (for 2.67 g·cm^{-3}), while the calculation of numerical derivatives of anomalous field ($\partial f/\partial x$, $\partial f/\partial y$, $\partial f/\partial z$) was done by means of the Fourier transformation (using the algorithm FFT in the Matlab programming language environment). We took the concept of the calculation of the regularized derivatives with the use of a choice of optimum parameter on the basis of the analysis of the C-norm (*Pašteka et al., 2009*), as the standard determination of the numerical derivatives greatly emphasized the noise in the original grid of the *CBA*. The calculation of transformed fields was implemented in the medium of the program REGTILT (*Pašteka et al., 2015*), which uses the concept of regularized derivatives with the use of other L_p-norms (*Pašteka et al., 2012*). Shapes of the evaluated C-norms for all three orthogonal derivatives (x-, y- and z-derivative) are displayed in Fig. 3 together with selected optimum values of regularization parameters (red circles in graphs in Fig. 3).

When looking at the results of these transformations for the *CBA* field of new generation (2.67 g·cm^{-3}) in Figures 4 to 10, it is seen that these fields respond to the manifestations of shallower density inhomogeneities. On the other hand, the effect of the Western Carpathian gravity low as well as in-

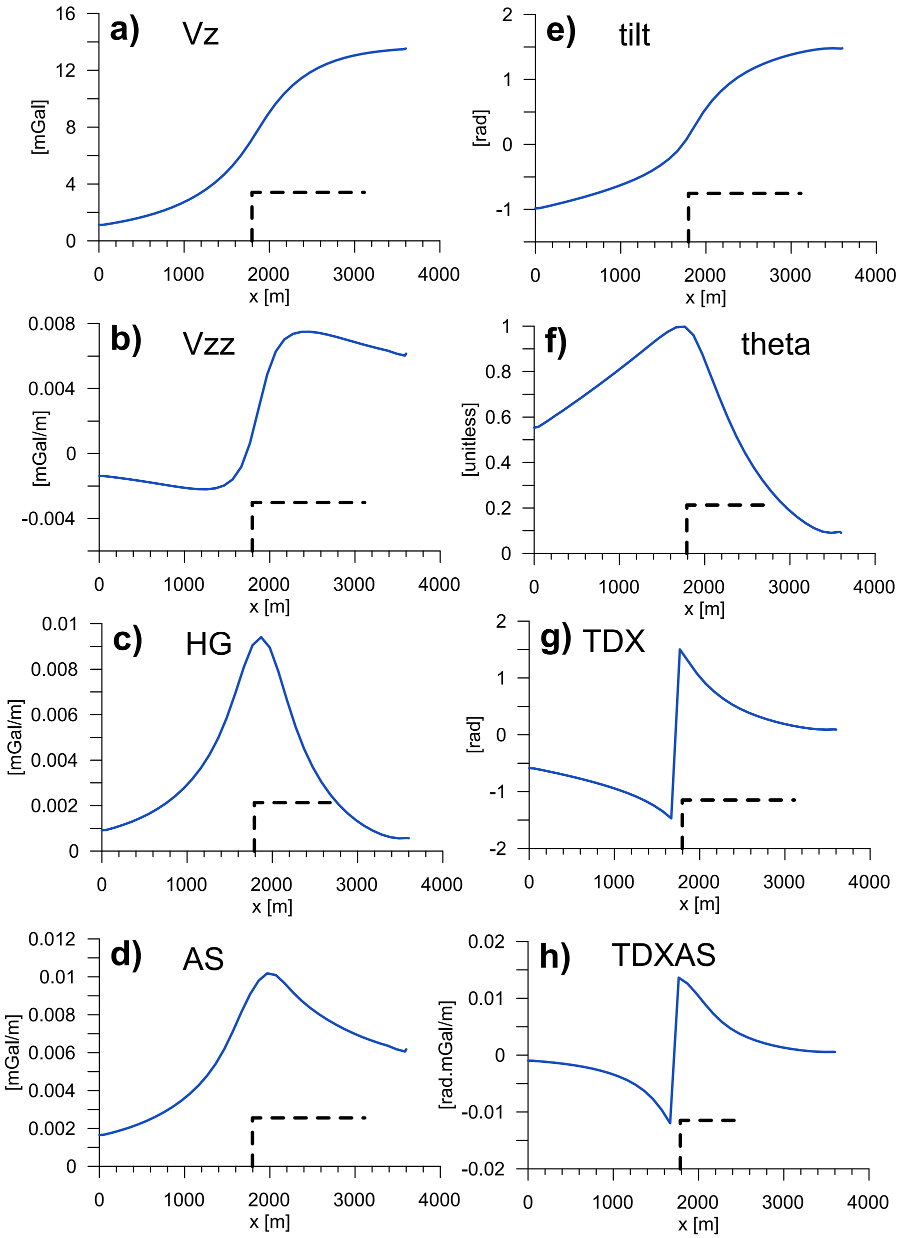

Fig. 2. The curves of the transformed field over the model of a rectangular step at the depth of 200 m below the surface and with density contrast of 0.4 g·cm^{-3}.

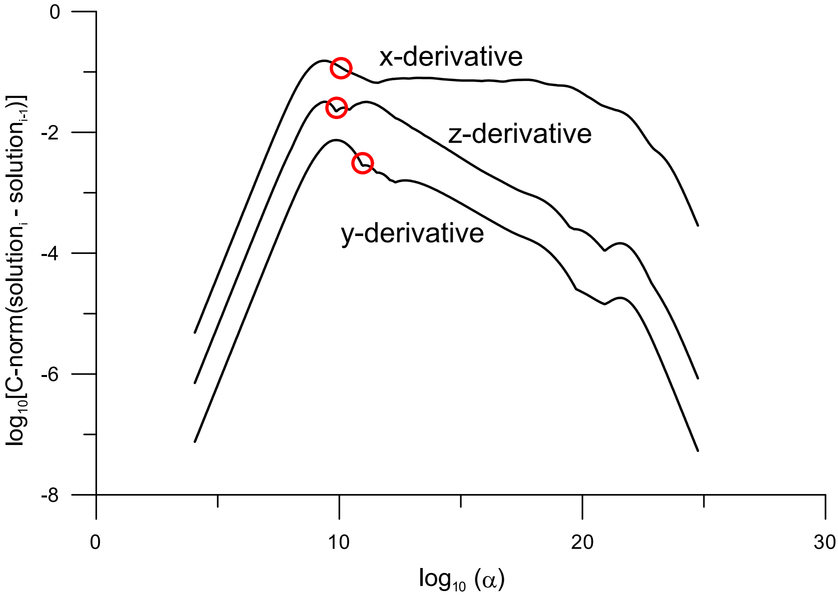

Fig. 3. Graphs of evaluated C-norms for the selection of the optimum regularization parameter during x-, y- and z-derivatives evaluation (optimum values are marked with red circles).

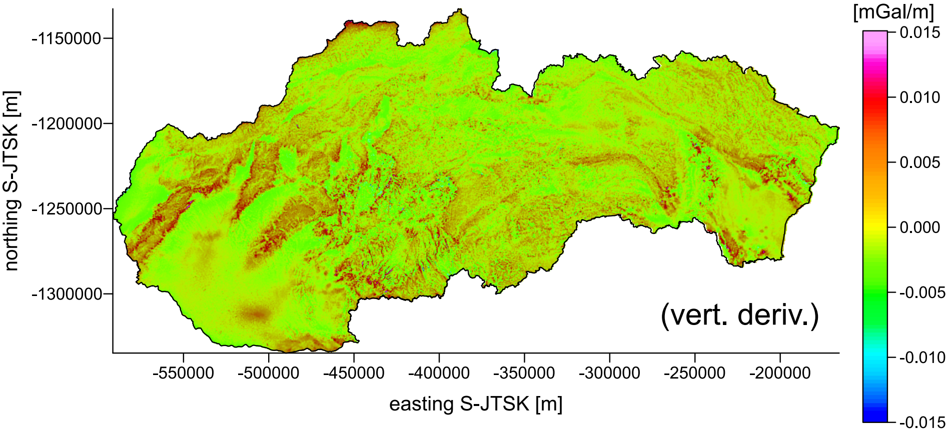

Fig. 4. Map of the vertical derivative for the *CBA* field of the new generation for the territory of the Slovak Republic (2.67 g·cm^{-3}).

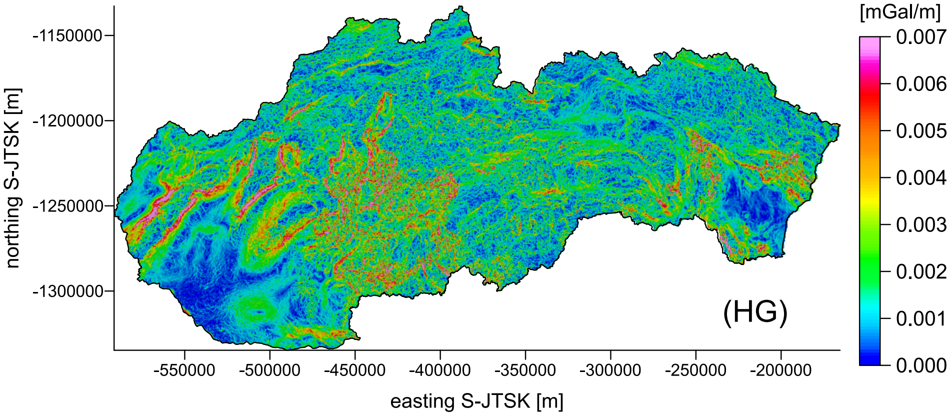

Fig. 5. Map of the horizontal gradient for the *CBA* field of the new generation for the Slovak Republic's territory (2.67 g·cm^{-3}).

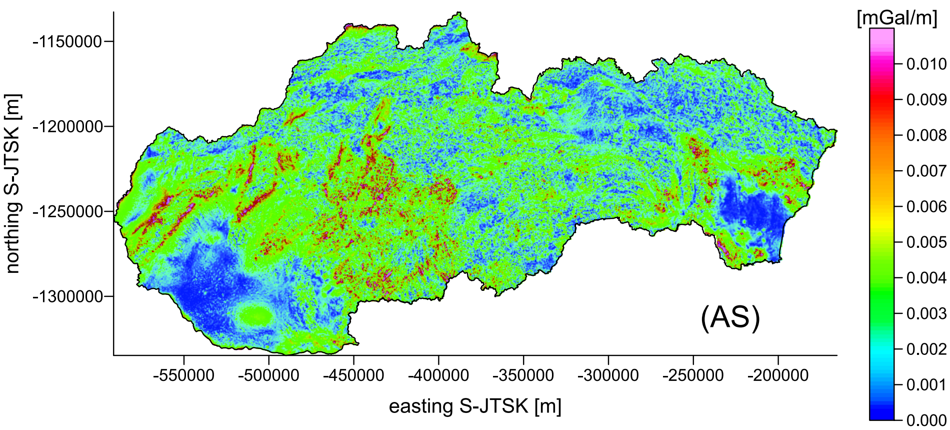

Fig. 6. Map of the analytical signal for the *CBA* field of the new generation for the Slovak Republic's territory (2.67 g·cm^{-3}).

creased anomalous values in the southern part of Slovakia due to the impact of the Panonian diapirism diminish in those fields (compare with Fig. 1). In most transformed fields, it can be seen that they highlight the dominant anomalies of the *CBA* (e.g., the manifestations of the Core Mountains: the Malé Karpaty Mts., Považský Inovec Mts., Tríbeč Mts. plus the boundaries of the intra-Carpathian basins in the western part of the territory; the expression of the Rakovec and Klatov groups of the Gemericum as well as the

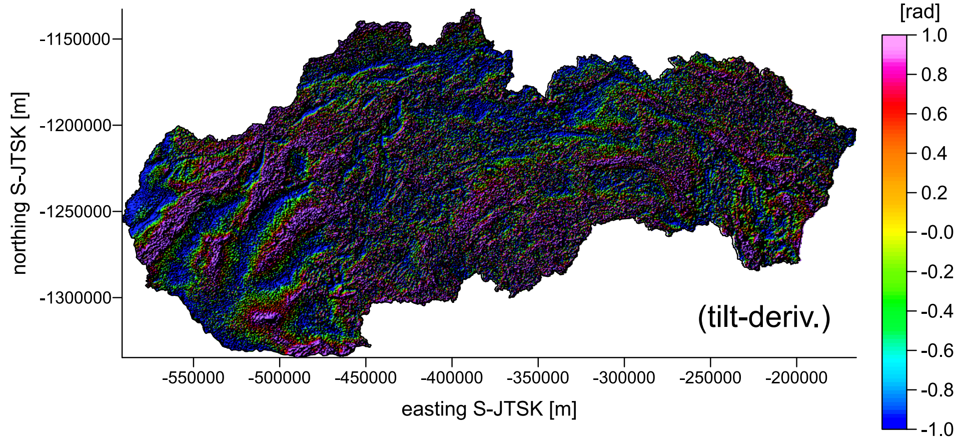

Fig. 7. Map of the "tilt"-derivative for the *CBA* field of the new generation for the Slovak Republic's territory (2.67 g·cm^{-3}).

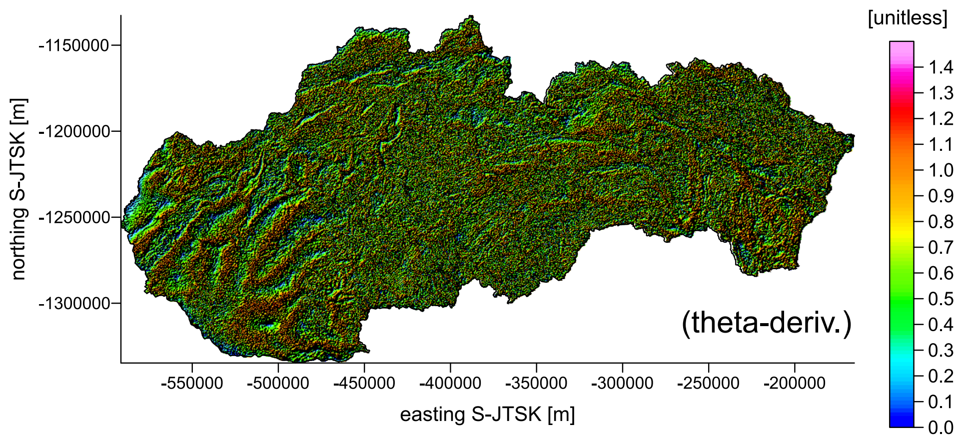

Fig. 8. Map of the "theta"-derivative for the *CBA* field of the new generation for the Slovak Republic's territory (2.67 g·cm^{-3}).

expression of the uplift of pre-Cenozoic basement of the Humenné Mesozoics and the parts of Zemplín Hills in the eastern part). In some transformed maps, it is not easy to see all the details of gravity field due to the large area view. Therefore, it is sometimes much better to concentrate on some crucial detail.

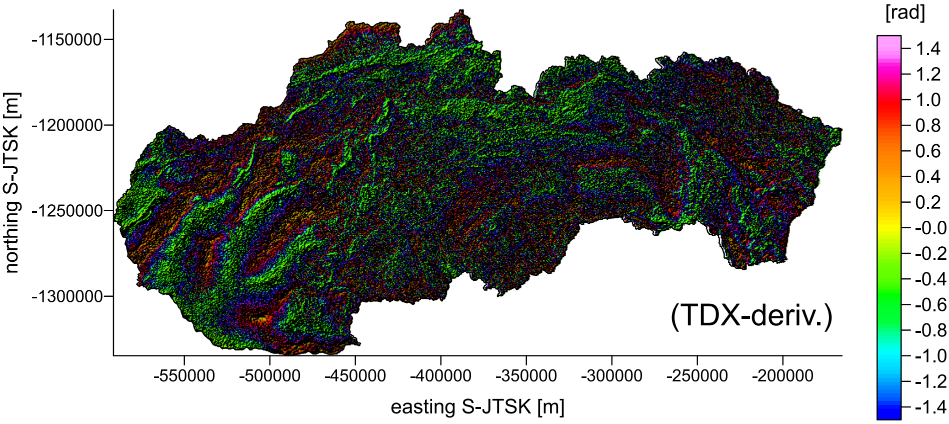

Fig. 9. Map of the *TDX*-derivative for the *CBA* field of the new generation for the Slovak Republic's territory (2.67 g·cm^{-3}).

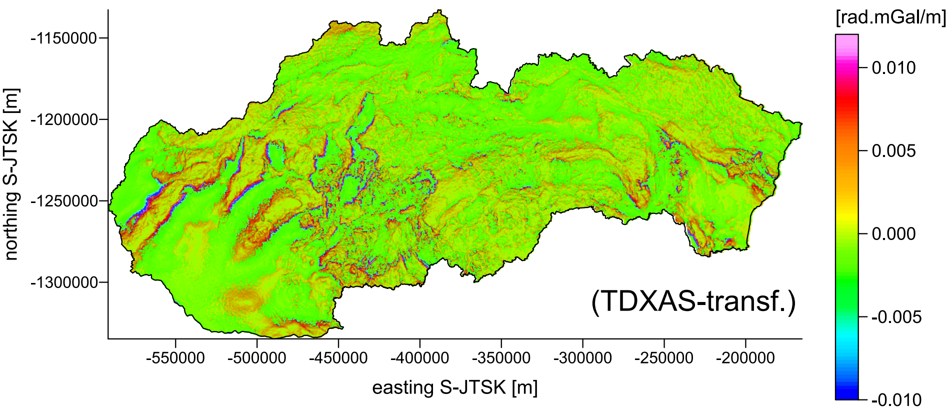

Fig. 10.Map of the *TDXAS*-transformation for the *CBA* field of the new generation for the Slovak Republic's territory (2.67 g·cm^{-3}).

4. Selected interpretation of transformed fields – a case study

As a case study, we demonstrate a part of the territory of Slovakia (Kysuce, Orava, Malá Fatra Mts. and Veľká Fatra Mts. with the Turiec Basin in the middle of the southern part – Fig. 11). It is possible to see that the transformed fields (the *HG* and *TDXAS* fields were selected) significantly respond to the occurrence of tectonic units in the lateral direction.

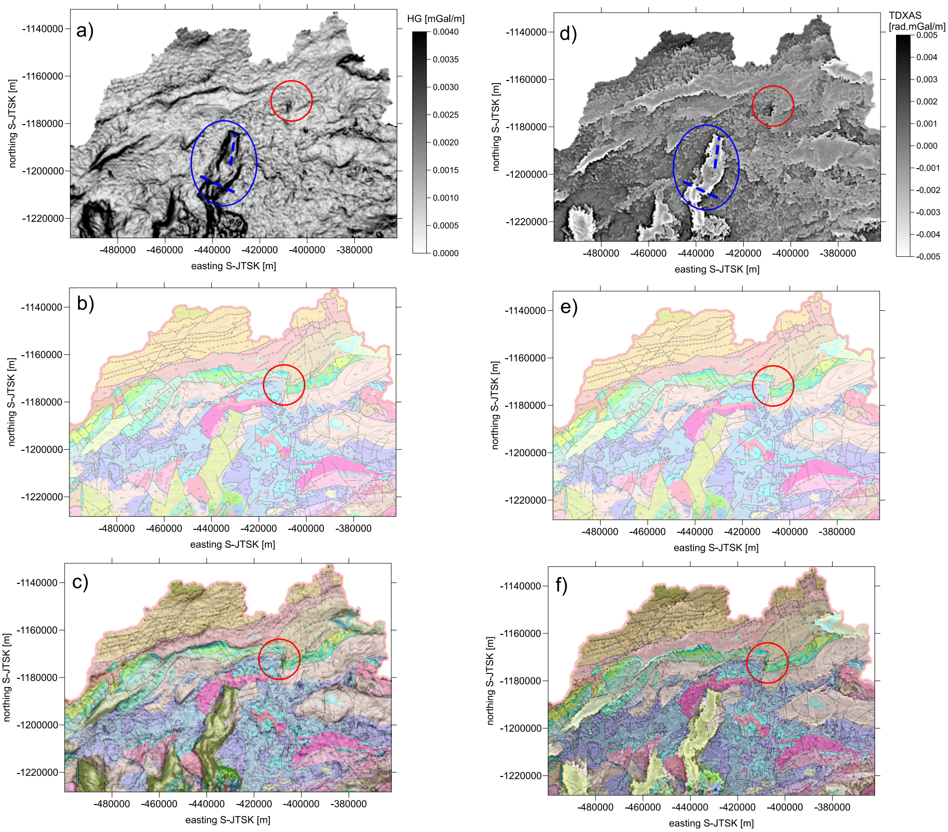

Fig. 11. Selected transformed fields (*HG* and *TDXAS*) for the NW part of Slovakia and their comparison with part of a tectonic map (*Bezák et al., 2004*).

In the northern part of the territory, the *HG* field (Figs. 11a-c) reacts to the contact of the Klippen Belt with the Magura part of the Flysch zone, including a well-recognizable Zázrivá sigmoid (the red ring in the partial figures in the Fig. 11). It is interesting to mention that the course of the contact of the Klippen Belt with its surrounding tectonic units is traceable really well. Apart from the above mentioned Turiec Basin it is also possible to see the manifestation of the Bánovce depression, Horná Nitra Basin and Ilava depression in the central part of shown territory. All of them are marked by significantly larger values in the field of the *HG* and are represented by isolated objects with lower values of the *TDXAS* field. The information value of the presented transformed fields can be very clearly demonstrated by the analysis of the features of the Turiec Basin basement in the field of the *HG* and *TDXAS* (Fig. 11). Here, it is very nice to see an expression of the Blatnica fault (separating the basin on the northern and southern part), which is demonstrated by the shifts of the local maxima. In the northern part, it is possible to recognize the manifestation of the Mošovce-Dulice fault, which divides the northern part into two different parts: western (composed of lower density Tatric complexes) and eastern (comprising higher density complexes of the Fatricum). These features are indicated by short dashed blue lines in Fig. 11a,d. The results correlate very well with interpretation of *Bielik et al. (2013).*

5. Conclusion

In the qualitative interpretation of fields of complete Bouguer anomalies, various visualization techniques (surface shadowing, adjustments of colour scales, etc.) are very useful. In addition, the calculations of various transformed fields (based on the determinations of the higher derivatives of the anomalous field and their ratios) help us, too. Looking at these results obtained by the calculation of the *CBA* field of the new generation (for 2.67 $g \cdot cm^{-3}$) for the whole territory of Slovakia, it is possible to see that the fields respond mostly to the expressions of shallow density inhomogeneities, while the effects of the Western Carpathian gravity minimum and the Pannonian gravity high decrease. In most of the transformed fields we can see that they emphasize the dominant anomalies of the *CBA* (the manifestations of some Core Mountains plus the boundaries of the intra-Carpathian Basins in the western part of the territory, the Spiš-Gemer Ore Mts., as well as the effect of the pre-Tertiary basement of the Humenské Mesozoics and parts of the Zemplín Hills in the eastern part).

From the detailed case study of the north-western part of Slovakia we can see clearly that the qualitative interpretation of the calculated transformed fields from the *CBA* field of the new generation represents a great potential for a study of the tectonic structure and the structural geological mapping of the Western Carpathians. These can also contribute to research on the sedimentary basement structure and the detection of areas, which are suitable for a prognosis of the hot dry rock energy sources. This process is still developing and is being discussed. In spite of this, the results represent exclusive geophysical interpretative materials for a study of the Western Carpathian geology. Grids of the presented transformed fields (GS Surfer format) are available for the scientific community and can be downloaded from the server: `http://www.kaeg.sk/vyskum/projekty-apvv/apvv-0194-10-bouguer_ng/`.

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