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NEO-ALPINE LINEAR DENSITY BOUNDARIES (FAULTS) DETECTED BY GRAVIMETRY

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Abstract: The use of gravimetry, as one of the geophysical methods for identification of brittle deformations — faults active during the neo-Alpine development of the Western Carpathians, confirmed its role in research of the orogene geodynamic evolution. The study of several sites in the western part of the Western Carpathians documents the fact, that the maps obtained by means of different effective gravimetric methods of transformations and visualization of gravity (potential field) data can be correlated well with the age, and thus also with the depth of the faults. The map of the total Bouguer gravity anomaly displays faults without distinguishing their age and depth. In such case the use of the Linsser method is proper for the detection of faults or density boundaries. While the derived maps, such as the vertical and horizontal gradients, and the residual anomaly maps, document the faults depending on the type of transformation and visualization of the input computation parameters. The results and interpretation indicate, that the map of residual anomalies displays mainly the deep faults of the initial rifting and of the synrift stage of the back-arc basin development and the map of the vertical gradient displays most of all the young shallow marginal faults and faults linked with the postrift thermal subsidence stage and tectonic inversion of the basin.

Key words: neo-Alpine tectonics, Western Carpathians, brittle deformations, linear density boundaries, gravimetry.

Introduction

Gravimetry can be used, in an applied form, for investigation of the geological pattern of the region, which means also for detecting the brittle tectonic deformations — faults (e.g. Linsser 1967a,b; Nettleton 1971; Garland 1979; Griffiths & King 1981; Fusán et al. 1987; Šefara et al. 1987; Murata & Noro 1994; Langenheim 1995; Wybraniec 1999; Nemesi et al. 1996).

The gravity gradients most often separate the boundaries of units, which vary in petrographic and/or density, and are the major indicators of tectonics on a gravimetric map. Their intensity is proportional to the density difference, the amplitude of the step, and the slope of the fault. For practical application, the density boundary (fault) is approximated by a simple geometric body (two-dimensional), the dimension of which along the fault is infinite (Nettleton 1971; Linsser 1967a,b; Pick et al. 1973; Griffiths & King 1981).

The principle of the method lies in calculation of the gradient function based on taking the derivative of the measured gravity data (V_z) either with respect to the *x* and *y* axes (horizontal gradient — V_{zx} or V_{zy} (HG)), or the *z* axis (vertical gradient — V_{zz} (VG)). The derivatives may be calculated by finite differences. The resulting maps are portrayed either in positions of the inflex points (by localizing the maxima of the amplitude of the gravity field gradient) or by isolines of the gradient moduli (Parasnis 1967; Pick et al. 1973; Lillie 1999; Wybraniec 1999).

The main goal of this study is to test the use of gravimetry as one of the geophysical methods for investigation of the neotectonics in the western part of the Western Carpathians (Fig. 1).

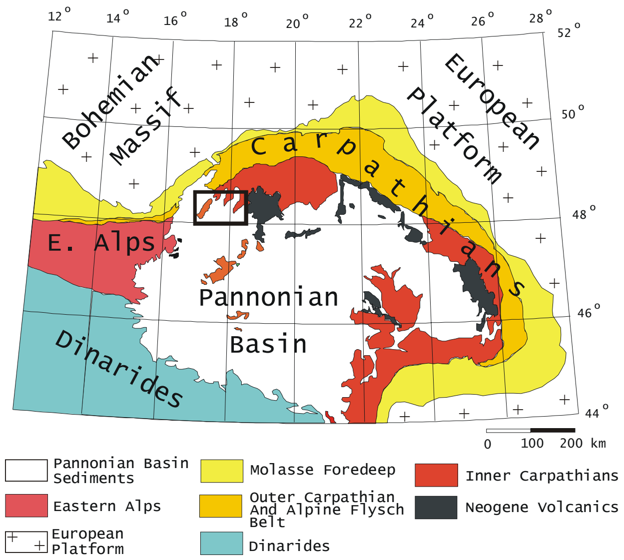

Fig. 1. Schematic tectonic map of the Eastern Alpine–Western Carpathian–Pannonian basin region (modified after Lillie et al. 1994). The studied area is shown by a frame.

That is also why we will deal only with those gravity field interpretation methods, that can contribute most to the indication of linear structures of the gravity field. In this paper, effective mapping methods of gravity data are described. The total Bouguer gravity anomaly map in combination with its transformed and visualized gravity data help us to understand the interdependent nature of the relationships of geological phenomena (Meskó 1985; Šefara 1989; Bielik 1982).

Methodology

The total Bouguer gravity anomaly is a superposition of the gravity effects of all the density inhomogeneities that are present under the surface of the studied region. The effect of inhomogeneities depends on their size, differential density, and the distance from the observation point (e.g. Torge 1989). In practice it often happens that the gravity effect of the anomalous body under our interest (here — the linear density boundary — fault) is partly or totally concealed by effects of other anomalous masses. This implies that the quality of the interpretation substantially depends on the quality of separating the gravity effect of the investigated fault from the Bouguer gravity anomalies. Generally, the anomaly may be divided at each point into two components: the regional and the residual. The regional (residual) component of the gravity is characterized by long-wavelength (short-wavelength) anomalies. Linear form of the Bouguer gravity anomaly (density boundary) produces a couple of positive/negative residual anomalies and the density boundary is going between them.

In gravimetry, the transformed maps (the derived or convolution maps) differ from the original maps of total Bouguer gravity anomalies by having the components of the original field, that concern us, pronounced (e.g. Ku et al. 1971; Meskó 1985; Pick et al. 1973; Šefara et al. 1987; Bielik 1982; Blakely 1996). Any transformation cannot bring a basically new information, it may, however, somehow extract and amplify what is already contained within the original map.

The use of the transformation method depends mainly on whether we deal with a shallow fault or a deep fault. When searching for shallow (deep-seated) faults, the interpreter must apply such transformation method, which pronounces the anomalies with short (long) wavelengths. The residual anomaly at the point of calculation was defined as the mean value of the anomaly on the surface of a circle (Griffin 1949; Pick et al. 1973). Digitization of gravity data for all transformed maps were performed in a grid of 200 m. When the radius for computing the mean is chosen suitably, it is possible, on the basis of the character of the anomalies of the gravity field of the transformed map, to find out at least indirectly, whether we are dealing with a shallow or a deep fault structure, and to estimate its depth.

The Linsser method (Linsser 1967a,b) has also been used for indicating the density boundaries. It is based on filtering the anomalous field by means of a comparison of a pre-determined theoretical anomalous effect of a certain model in the measured gravity field (Šefara 1973, 1989). When solving the directional characteristics of the anomalous gravity field, we follow a model of the vertical density boundary (massive half-space), which appears the most suitable for approximating linear geological structures. The defined indications of the vertical density boundaries are the output data. If these indications fall into certain lines, we can essentially interpret them as the vertical, or slanted density boundary of a linear shape — fault. If these indications on the maps are non-linear, then they feature more probably the presence of three-dimensional bodies.

The maps of the vertical or horizontal gradient represent a significant group of transformed maps suitable for solving the structural-tectonic relationships. In the vertical gradient (VG) maps we find a pair of bands of opposite sign values over the sub-vertical density boundaries. The excess masses feature negative anomalies in the VG while the masses deficient feature positive VG anomalies, (opposite to the input of the total Bouguer gravity anomaly map). The vertical gradient of the total Bouguer gravity anomaly is generally sensitive to shallower density inhomogeneities, compared to the horizontal gradient. The paths of the signatures of tectonics need be drawn on the boundary separating positive and negative anomaly bands. The VG responds to the density fill of the shallow volumes with anomalies of signs opposite to those of the input total Bouguer gravity anomaly map or the local anomaly map.

The maps of the horizontal gradient (HG) normally have maxima over the subvertical density boundaries, which originate, for instance, above the margins of sedimentary basins or above contacts of intrusive bodies (suppose these are not horizontal), as well as above fault systems, along which blocks with varied density evolution were trapped next to each other as a result of tectonic movements. The shape of the gravitational effects of such density boundaries implies that the ability of the HG to respond to such effect must be high for various depth ratios of the boundaries. The boundaries may (or may not) be visible already on the surface of the earth and may (or may not) continue to great depths exceeding the radius of the analysed area of the computation point. Usually the HG maxima arrange themselves on the map into bands. The paths of such bands are identical with the paths of centres of surfaces of the subvertical density boundaries. The minima on the HG maps represent blocks, in which the density changes are presented only in a vertical direction, if at all.

Detection of linear density boundaries

The suitability of the individual interpretation methods was reviewed on a gravimetric and database file from the area of western Slovakia, namely at the eastern margin of the Vienna Basin, Malé Karpaty Mts horst, in the Danube Basin, the Považský Inovec Mts and the Tribeč Mts horsts (Fig. 2). For detecting the regionally significant fault systems we have used the map scale 1:500,000 (Fig. 2). To verify the details of the geological pattern of the area of the Zohor-Plavec Trough that is superposed over the system of the Leitha faults (Fig. 2) and in the area of the Považie fault system (Figs. 3, 4) we have originally used the map scale of 1:100,000.

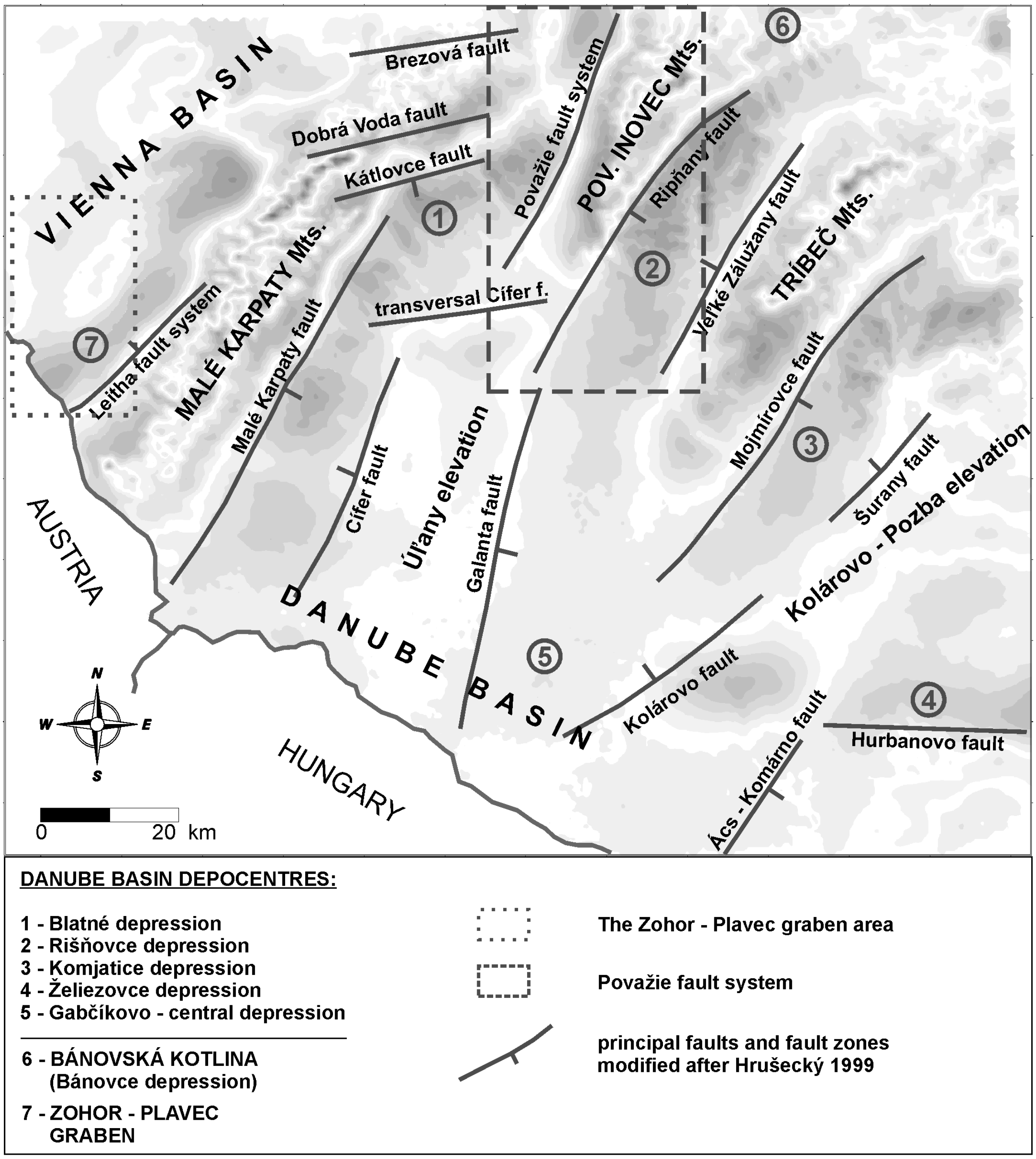

Fig. 2. The main structural and tectonic features of the western part of the Western Carpathians. The background of the figure is a scheme of the residual gravity map (R = 12,000 m with a grid of 200 m). Red colour represents positive values of gravity anomalies. Blue represents negative values.

Linear density inhomogeneities indicated by various types of regional gravimetric maps

Map of total Bouguer gravity anomalies

The figure 3A documents the distribution of the linear gravity elements, as well as of the low-density and high-density masses in the western part of the Western Carpathians. The NE-SW trending eastern margin of the Vienna Basin is particularly pronounced at the boundary with the Malé Karpaty Mts horst, as are the boundaries of the Malé Karpaty Mts horst and the Považský Inovec Mts horst against the Danube Basin. The ENE-WSW oriented margin of the southern and northern boundary of the Blatné Depression of Danube Basin (transversal Cífer fault and the Kátlovce fault, of the same direction as the Brezová and Dobrá Voda fault system), as well as the fault system at the boundary between the Rišňovce Depression of the Danube Basin and the Bánovce Depression are also appar-

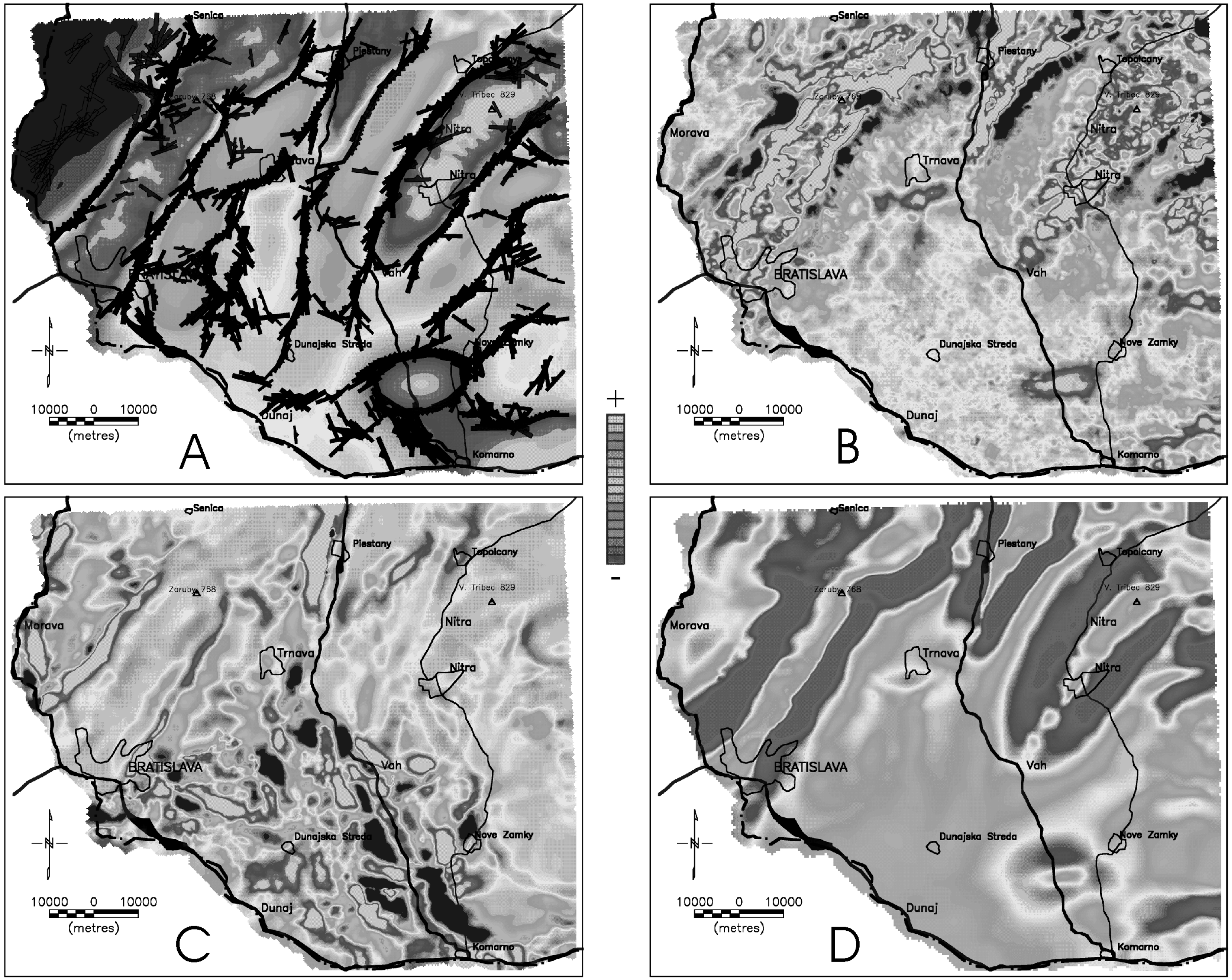

Fig. 3. Regional gravimetric maps. **A** — map of total Bouguer gravity anomalies (after Šefara et al. 1987, the values of gravity anomalies vary from −40 to +34 mGal) and map of indications of vertical density boundaries [Linsser, h = 2000 m and $\Delta\sigma$ = 150 kg.m^{-3}; the grid of gravity values is 200 m, size of marks is in accordance with the size of parameters *E* and *C* defined by Linsser (1967a,b) and Šefara (1973)], **B** — map of residual gravity anomalies (R = 4000 m with a grid of 200 m, the values of gravity anomalies vary from −6 to +8 mGal), **C** — map of vertical gradient [R = 4000 m with a grid of 200 m, the values vary from −5200 to +5500 E (1 Eötvös = 1 mgal/10 km = $10^{-9}s^{-2}$], **D** — map of horizontal gradient (R = 3000 m with a grid of 200 m, the values vary from +1 to +77 E).

ent (Fig. 2). The picture of the southern part of the territory documents the presence of high-density masses in the Kolárovo anomaly area, whereby the effect of the Transdanubian Range Unit is pronounced only to the east of Komárno (the Komárno block sensu Hrušecký 1999).

Map of indications of vertical density boundaries — Linsser

This map (Fig. 3A) well documents the deep and the shallow boundaries, the linear course of which entitles us to interpret them as neo-Alpine brittle deformations — faults. The fault boundary of the Malé Karpaty Mts horst with respect to the Vienna Basin (the Leitha fault system) and the Blatné Depression of the Danube Basin (the Malé Karpaty fault) are easily observable. Next, the Považie and Ripňany faults are clearly visible and mark the eastern and western slopes of the Považský Inovec Mts horst. In the western part of the Gabčíkovo Depression, the NNE-SSW oriented systems of Cífer faults dipping towards the west are particularly pronounced, as well as the Galanta faults dipping towards the east and they represent margins of the Úľany elevation (sensu Hrušecký 1999). Towards the south, in the Hungarian part of the basin, we assume a connection to the Mihályi elevation which is bounded by the Répce fault system (sensu Tari et al. 1992).

The Tribeč Mts horst boundary is also well documented, by the Veľké Zálužany fault system in the west and by the Mojmírovce fault system in the east (Fig. 2). The Komjatice Depression boundary is formed by the Mojmírovce faults in the north-east and by the Šurany fault system in the south-east, in the continuation of which the Kolárovo faults are located in the Gabčíkovo Depression, with the same NW dip (Hók & Ivanička 1996). The picture of the eastern part of the Danube Basin is unclear. In the prolongation of the Ács-Komárno fault system, there are faults limiting the eastern margin of the Kolárovo–Pozba horst of the NE–SW direction (Hrušecký 1999). The Hurbanovo fault, or the northern margin of the Transdanubian Range Unit are only partly visible.

Map of residual anomalies

The residual anomaly map with the radius of taking the mean 4 km (Fig. 3B) documents the deep fault boundary of the eastern margin of the Vienna Basin with respect to the Malé Karpaty Mts horst, characterizing the boundary between the Eastern Alpine and Western Carpathian units along the left-lateral shear zone — the Leitha fault system (sensu Marko & Jureňa 1999).

Next we easily trace the pronounced boundary at the eastern slopes of the core mountains horsts: Malé Karpaty Mts, Považský Inovec Mts and Tribeč Mts (Malé Karpaty, Rišňovce and Mojmírovce fault systems). Unpronounced are the fault systems in the basement below the Danube Basin fill. The elevation structures of the Úľany and Kolárovo-Pozba (Hrušecký 1999) are indicated only partly, like as the Transdanubian Range Unit in the eastern part of the basin. One could conclude, that the map pronounces the deep-seated Neogene faults at the eastern slopes of the core mountains compensating the movement along the listric décollement at the boundary of the rigid and ductile part of the crust during the Danube Basin opening (the Wernike's model used for the formation of the Danube Basin sensu Horváth 1993; Lankreijer et al. 1995). The prolongation of these faults in the central part of the basin is indistinguishable, clearly due to the disturbing effect of the sedimentary fill of the Danube Basin, which reaches thickness of up to 8 km (Kilényi & Šefara 1989).

Map of vertical gradients

On the map of vertical gradients with a mean radius of 3 km (Fig. 3C) there are linear inhomogeneities — faults indicated by the contact of negative and positive anomalies. On the map, the boundary at the eastern margin of the Vienna Basin is demonstrated with a pronounced signature of the Leitha faults in the area of the Zohor–Plavec graben at the western margin of the Malé Karpaty Mts horst. The next very pronounced contact represents the fault boundary of the western margin of the Považský Inovec Mts horst (Považie faults) and the western margin of the Tribeč Mts horst (Veľké Zálužany fault). The Malé Karpaty and Ripňany fault system at the eastern margin of the core mountains is less clearly (Fig. 2).

On the other hand, the NW–SE oriented linear elements of the same intensity multiply; these can be interpreted as a documentation of structural deformations (faults, flexures) known only in the youngest sediments of the Danube Basin (Hók et al. 1999). The projection of the margin of the Transdanubian Range Unit onto the surface is apparent with the same intensity in the area of the Hurbanovo fault zone. If the map of the residual anomalies is compared with the map of the vertical gradient, it seems that the vertical gradient documents much better the younger and shallower faults and structural deformations (flexures due to compaction of sediments of various grain size) in the sedimentary fill of the Vienna and Danube Basins in Slovak territory, that is the tectonics of the Upper Miocene to Pliocene-Pleistocene age.

Map of the horizontal gradient

The horizontal gradient map (Fig. 3D), as was already noted in the methodology, contains mainly the maxima above the appearances of subvertical density boundaries situated near the margins of sedimentary basins in the western part of the Western Carpathians. The map ignores the depth reached by faults (and thus indirectly also their age and causes). All faults on the peripheries of the core mountains are clearly visible: the Leitha, the Malé Karpaty, the Považie, the Rišňovce, the Veľké Zalužany and the Mojmírovce fault systems separating the partial depocentres of the Danube Basin: the Blatná, the Rišňovce, and the Komjatice depression (Vass et al. 1990; Hók et al. 1999). The interesting elements include the N-S running of subvertical boundaries (depressions) in the central part of the basin that can be compared to the direction of the Cífer and Galanta faults, and the boundary of NE–SW direction comparable with the Čertovica-Mojmírovce fault system (Hrušecký 1999).

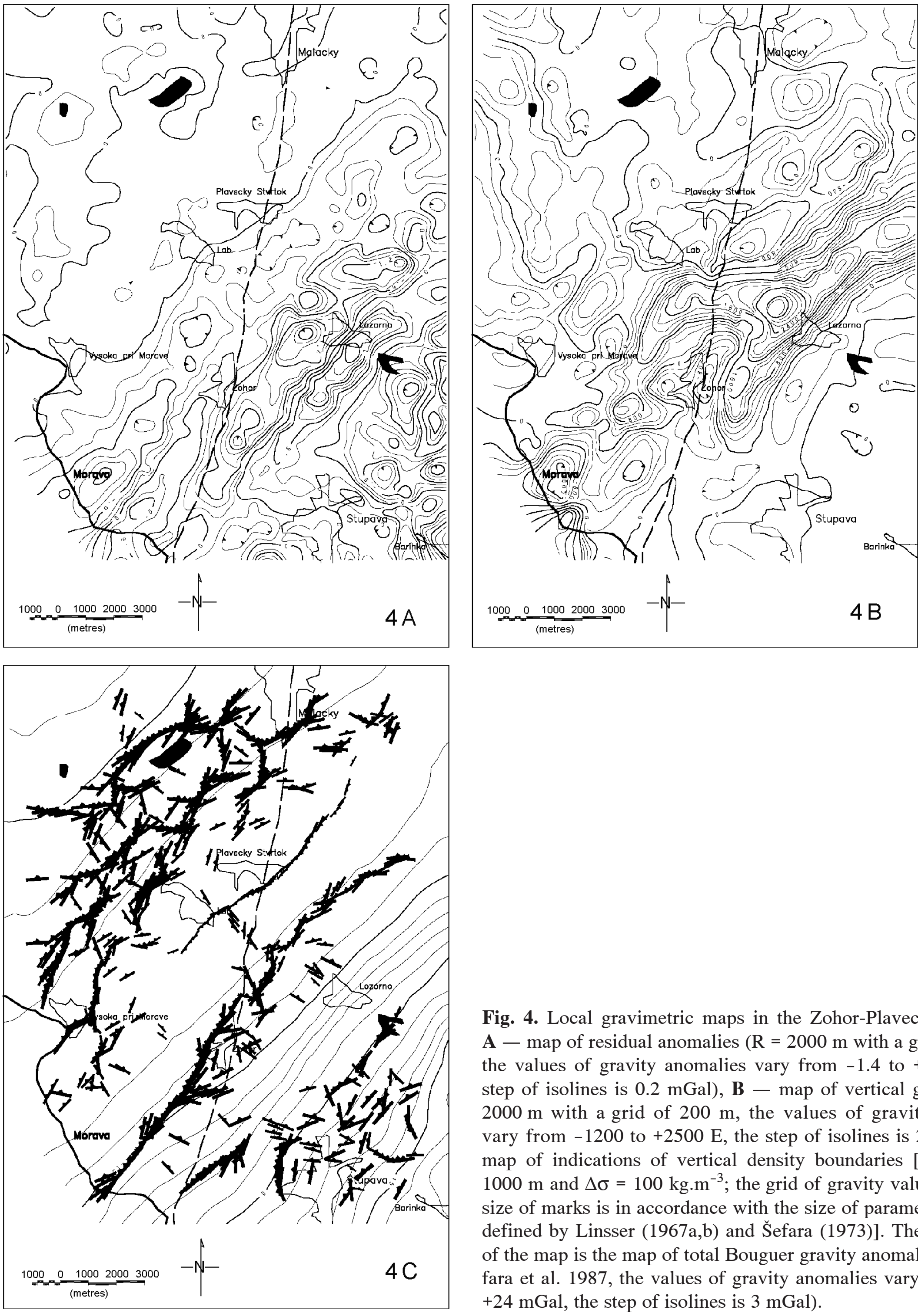

Fig. 4. Local gravimetric maps in the Zohor-Plavec graben area **A** — map of residual anomalies (R = 2000 m with a grid of 200 m, the values of gravity anomalies vary from –1.4 to +1.6 mGal, a step of isolines is 0.2 mGal), **B** — map of vertical gradient (R = 2000 m with a grid of 200 m, the values of gravity anomalies vary from –1200 to +2500 E, the step of isolines is 200 E), **C** — map of indications of vertical density boundaries [Linsser, h = 1000 m and $\Delta\sigma$ = 100 kg.m^{-3}; the grid of gravity values is 200 m, size of marks is in accordance with the size of parameters *E* and *C* defined by Linsser (1967a,b) and Šefara (1973)]. The background of the map is the map of total Bouguer gravity anomalies (after Šefara et al. 1987, the values of gravity anomalies vary from –33 to +24 mGal, the step of isolines is 3 mGal).

Linear density inhomogeneities indicated by various types of local gravimetric maps

The Zohor-Plavec graben area

As on the regional gravimetric maps (Fig. 3A–D), the significant element on the detailed (local) gravimetric maps is the Leitha faults of NE-SW direction (Fig. 4A–C). On the map of indications of density boundaries — Linsser (Fig. 4C), as well as on the residual anomaly map (Fig. 4A), however, we also find the crosswise physical boundaries interpreted as older faults of the NW-SE direction activated during the early neotectonic stage of development of the studied region. The interesting elements also include the boundaries located in the up-

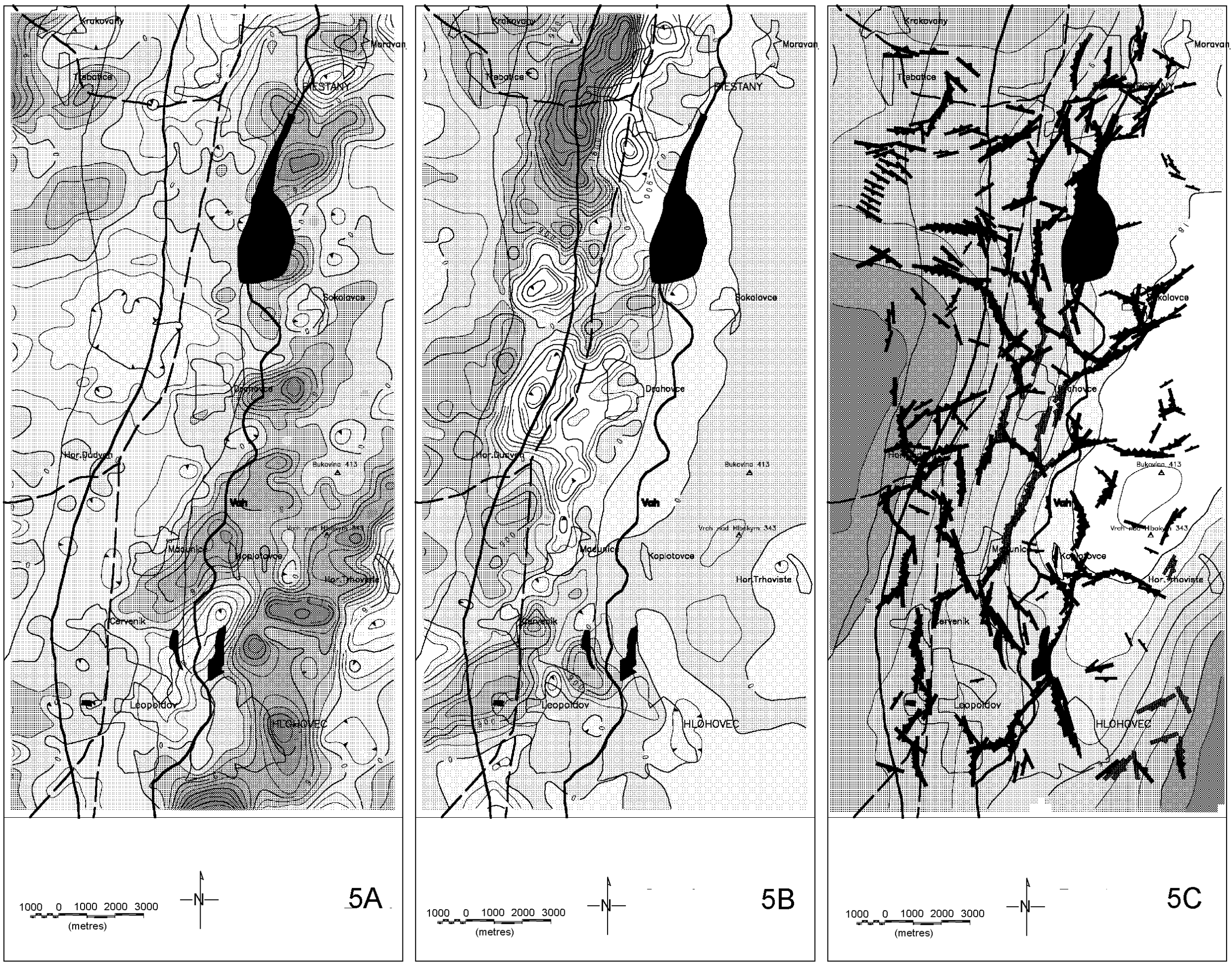

Fig. 5. Local gravimetric maps in the Považie fault system region. **A** — map of residual gravity anomalies (R = 2000 m with a grid of 200 m, the values of gravity anomalies vary from −1.4 to +3 mGal, the step of isolines is 0.3 mGal), **B** — map of vertical gradient (R = 2000 m with a grid of 200 m, the values of gravity anomalies vary from −3400 to +6000 E, the step of isolines is 600 E), **C** — map of indications of vertical density boundaries [Linsser, h = 1000 m and $\Delta\sigma$ = 100 kg.m^{-3}; the grid of gravity values is 200 m, size of marks is in accordance with the size of parameters *E* and *C* defined by Linsser (1967a,b) and Šefara (1973)]. The background of the map is the map of total Bouguer gravity anomalies (after Šefara et al. 1987, the values of gravity anomalies vary from −6 to +21 mGal, the step of isolines is 3 mGal).

per left half of the figure, probably representing the structural pattern (folds) of the Northern Calcareous Alp nappes in the pre-Neogene basement of the Vienna Basin (Fig. 4C). The residual anomaly map (Fig. 4A) best documents the tectonic components within the graben (division into partial depressions), whereas the vertical gradient map (Fig. 4B) indicates, the presence of young tectonic structures with an ENE-WSW direction, as well as the presence of the NE-SW faults.

The Považie fault system

The dominant elements on the local gravimetric maps (Fig. 5A–C) are the inhomogeneties in the N-S and NNE-SSW direction (the Považie fault). These inhomogeneities — faults are accompanied also by faults of the NW-SE to ENE-WSW direction. The most pronounced is the Koplotovce fault, which is located in the continuation of the Kátlovce fault system. Since, apart from the presence of the NNE-SSW faults, the vertical gradient map (Fig. 5A–B) also indicates, the presence of structures with the ENE-WSW direction, clearly visible on the map of density boundary indications — Linsser (Fig. 5C), we consider that they are associated with the Pliocene-Quaternary reactivation.

Neo-Alpine development of the Western Carpathians as indicated by means of different transformed gravity maps — a discussion

The neo-Alpine development of the Western Carpathians and the adjacent part of the Pannonian back arc basin is characterized by several stages of development:

A — In the Early Miocene the oblique collision of the Western Carpathian orogen with the Bohemian Massif played the key role. The compression initiated the northward movement of the ALCAPA microplate (ALCAPA — Alpine-Carpathian-Pannonian block assemblage) eastern segment and caused fold–nappe tectonics with formed the accretionary prism of the Outer Carpathians. Dextral shears with an ENE–WSW direction were activated in the same stress field. In the area of the

Central Western Carpathians, they led to opening of sedimentary basins of wrench fault furrow type (Kováč et al. 1989; Kováč & Márton 1998; Kováč et al. 1997, 1998). These tectonic structures can be compared with the oldest detected linear density inhomogeneities — faults in the studied area (the Brezová and Dobrá Voda, Kátlovce and the transversal Cífer fault systems), the activity of which is assumed from the Eggenburgian to Karpatian. They are manifested in the total Bouguer gravity anomaly map, in the vertical density boundary map — Linsser and partially in the residual anomaly map (Figs. 2, 3).

B — At the end of the Early and beginning of the Middle Miocene the ALCAPA microplate extruded eastward (Ratschbacher et al. 1991a,b). The disintegration of the microplate was accompanied by the separation of the Western Carpathian units moving in the NE direction from the Alpine units. The zone of the Leitha faults at the eastern margin of the present Vienna Basin is regarded as the boundary between the units of the Eastern Alps and Western Carpathians. The extrusion was accompanied by initial rifting, mostly by opening of pull-apart type depocentres in the Vienna Basin and in the Blatné Depression of the Danube Basin (Royden 1993; Fodor 1995; Lankreijer et al. 1995; Kováč et al. 1997; Hrušecký 1999).

The area of the left lateral shears (transform system of the Leitha faults) makes up for a pronounced physical boundary between the Eastern Alpine and Western Carpathian units, which is well documented by all gravimetric maps. Its amplification in the vertical gradient map indicates at the same time its recent activity documented also by other geological and geophysical methods (Gutdeutsch & Aric 1988; Hók et al. 2000). It is well known, that here we are dealing with one of the most pronounced geophysical anomalous zones — discontinuities in the crust of the Western Carpathians (Labák & Brouček 1996; Šefara et al. 1998; Hók et al. 2000).

C — In the Middle Miocene a large back-arc extension took place, which is manifested by a synrift stage of the Vienna and Danube Basins development (Lankreijer et. al. 1995; Lankreijer 1998; Kováč 2000). On the basis of the seismic picture, in the Slovak part of the Danube Basin (Hrušecký 1999), as in its Hungarian part (Tari et al. 1992; Horváth 1993) the core mountain blocks tilting mechanism is applied above a deep zone of detachment (Wernicke's model of simple shear (Wernicke 1985; Lankreijer 1998)). We regard the brittle deformations at the eastern margin of the core mountains as the main normal faults, their respective pair systems being the faults at the western boundary of the Považský Inovec Mts horst, the Úľany elevation and the Tribeč Mts horst. These, however, do not have such a deep reach into the pre-Neogene basement.

The linear structures of the gravity field — identical with the course of the main faults of the synrift stage in the studied region are the Malé Karpaty, the Ripňany and Galanta faults, and the Mojmírovce faults systems. Their effect is clearly visible in the residual anomaly map, where, however, the prolongation of the Ripňany faults into the Galanta fault system is not manifested, because the Galanta fault system is covered by the very thick fill of the Danube Basin, as in the case of the prolongation of the Mojmírovce fault system into the Kolárovo system (Figs. 2, 3).

D — During the Late Miocene to Pliocene, in period of the postrift thermal subsidence the function of faults was pronounced at the margins of the rising core mountains (generally of NNE-SSW to NE–SW directions). In the Pliocene to Quaternary, the period of tectonic inversion of the back-arc basin (Horváth 1993; Bada 1999) a new group of tectonic structures entered the game. These fault's are limited to the Pliocene–Quarternary sedimentary area of the Slovak part of the Danube Basin (flexures, shallow faults). The Pliocene and the Early Pleistocene stress field can be characterized by extension in the NW–SE direction. Following the Early Pleistocene an extension of the NE–SW direction takes place (Hók et al. 2000; Kováč et al. in press).

The pronounced activity of faults at the margins of the core mountains is well documented by the horizontal gradient map (Fig. 3D). On the contrary, the vertical gradient map (Fig. 3C) pronounces faults that were active in the Pliocene-Quarternary period. The function of these faults is significantly manifested at the western margin of the core mountains (the Leitha, Inovec, Veľké Zálužie faults).

Conclusions

Gravimetric methods can be used effectively to indicate linear density boundaries, which can be interpreted as rigid deformations — faults of the neo-Alpine period of orogen formation (complemented by other geophysical and geological methods).

The map of indications of vertical density boundaries — Linsser, and the horizontal gradient map (Fig. 3A) pronounces all fault boundaries independently of age and depth. Its advantage is that it also documents the faults that are covered by a thick sedimentary fill of the Neogene basins.

The residual anomaly map (Fig. 3B) pronounces the Neogene (Miocene) faults reaching greater depths, they originated in the stage of the initial rifting and in the synrift stage of basin formation in the western part of the Carpathians (Vienna and Danube Basins).

The vertical gradient map documents younger and shallower faults at the margins of the core mountains, as well as structural deformations (flexures caused by compaction of sediments of various grain size) in the sedimentary fill of the Vienna and Danube Basins in the territory of Slovakia. There faults represent the tectonics of the Late Miocene to Pliocene-Pleistocene time.

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