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THREE-DIMENSIONAL QUANTITATIVE INTERPRETATION OF GRAVITY ANOMALIES IN THE SOUTH-WEST PART OF THE MALÉ KARPATY MTS. (WESTERN CARPATHIANS)

MIROSLAV BIELIK[1], ANNA SITÁROVÁ[1], DUŠAN PLAŠIENKA[2] and MARIÁN PUTIŠ[3]

[1]Geophysical Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 842 28 Bratislava, Czecho-Slovakia
[2]Geological Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 842 26 Bratislava, Czecho-Slovakia
[3]Department of Mineralogy and Petrology, Faculty of Sciences, Comenius University, Mlynská dolina, Pav. G, 842 15 Bratislava, Czecho-slovakia

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Abstract: Two independent methods of 3D quantitative interpretation were applied to local gravity highs induced by amphibolitic bodies in the pre-Alpine crystalline basement of the Tatric Bratislava Nappe in the Malé Karpaty Mts. Best-fit models show a uniform crescent shape of steeply dipping anomalous bodies in vertical cross-sections. This shape is interpreted from a tectonic point of view as a result of inversion tectonics and overthrusting, producing large-scale recumbent folds at the basement/cover interface in the frontal parts of the allochthonous Bratislava sheet.

Key words: Western Carpathians, Malé Karpaty Mts., Tatric basement, gravity anomalies, 3D modelling, recumbent fold, tectonic interpretation.

Introduction

Special attention has been paid to the Malé Karpaty Mts. from geologists and geophysicists of several specializations during the last decade. Careful petrological, geochemical and structural investigation was carried out in the crystalline basement (e.g. Korikovsky et al. 1984; Cambel & Vilinovič 1987; Putiš 1987) and sedimentological, biostratigraphical and tectonic studies in the Mesozoic complexes (Michalík 1984; Michalík et al. 1989; Mišík 1986; Mišík & Jablonský 1978; Plašienka 1987 etc.). Review papers of Maheľ (1983, 1987), Maheľ et al. (1987), Plašienka & Putiš (1987), Plašienka et al. (1991) and Kováč et al. (1991) summarize the present-day views on the structure and composition of rock complexes, which build up these areally small, but geologically important mountains linking the Alps and Carpathians.

Geophysical research also accelerated in the Malé Karpaty Mts. and their surroundings some years ago (e.g. Bárta et al. 1989; Šefara et al. 1987; Pěničková et al. 1989; for the review see Šefara in Kováč et al. (1991) and at the same time some parts of the mountains became a test area for interpretation and modelling of certain anomalies in physical fields (e.g. Bielik & Sitárová 1986). Among them, the Bouguer gravity anomalies as seen on the 1 : 25 000 map (Szalaiová et al. 1982) are locally clearly linked to distinct geological bodies visible on geological maps.

Local positive gravity anomalies in the crystalline basement are induced by mafic metavolcanic complexes (amphibolites - metabasalts, metagabrros, metatuffs) conformably surrounded by metasedimentary rocks. The results of 3D interpretation of the depth reach of the largest amphibolite body in the middle part of the Malé Karpaty Mts. (Bielik & Sitárová 1986) confirmed the usefulness of a best-fit quantitative modelling and revealed a surprisingly good agreement with the tectonic interpretation of the area. To test the method of a 3D inverse problem of gravimetry in some other areas with amphibolite-produced gravity anomalies we have applicated it to some small local anomalies in the SW part of the mountains (Fig. 1). Anomalies A (locality Hrubý pleš hill), B (Holý vrch hill) and C (Dúbravská hlavica hill and Brižité ridge) are confined to the apical parts of steeply dipping tabular bodies of amphibolites. The main aim of this contribution is to find out the subsurface shape of these bodies and their maximum depth reached in several profiles. The results of the best-fit modelling are discussed from the point of view of the regional tectonics and structual evolution of the area under consideration.

Geological setting

The Malé Karpaty Mts. appear to be a post-Paleogene asymmetric horst structure trending NE - SW separating the large Neogene Vienna Basin to the NW and the Danube Basin to the SE (Fig. 1). In the horst all principal basement and cover units of the outer part of the Central Western Carpathians are outcropped, namely the Tatricum formed by pre-Alpine crystalline basement and its Mesozoic cover and Late Paleozoic - Mesozoic décollement cover nappes, i.e. the Krížna (Vysoká), Choč and higher ones. The main features of the nappe stack were created during the Upper Cretaceous (eo-Alpine) shortening, which progressed from low-angle nappe overthrusting, through upright folding to a dextral transpression and backthrusting in the northern part of the Malé Karpaty Mts. (Plašienka 1989; Plašienka et al. 1991). The scarce Upper Cretaceous and Paleogene cover is confined to this transpressive belt.

The investigated area is located on SW slopes of the southern part of the Malé Karpaty Mts. in the vicinity of Bratislava (Fig. 1). Besides Cenozoic cover, rocks outcropped at the surface belong to two independent Tatric units: the lower - subautochthonous Borinka unit represented only by Jurassic sediments, and the higher - allochthonous crystalline basement rocks of the Bratislava Nappe sheet. The basement rocks are composed of Early Paleozoic (mostly Devonian) metasediments and metavolcanics, which form two Variscan units: the lower - Pezinok succession includes paragneisses, graphitic schists, metaquartzites and investigated bodies of metabasalts and their metatuffs; the upper - Marianka succession contains phylites, metagreywackes and greenschists (Putiš in Kováč et al. 1991; Plašienka et al. 1991). The bedding and schistosity is parallel to the Variscan overthrust plane, which was not rejuvenated during the Alpine deformations. The gneisses of the lower unit are penetrated by granitoids of the Bratislava pluton further to the SE (Fig. 1).

The gravity anomalies studied, are induced by bodies of mafic volcanics and volcanoclastics, several tens to hundreds of metres thick embedded in pelitic and psammitic sediments, all metamorphosed under low to medium grade conditions. The surface attitudes indicate steep NW dip of bedding and bedding parallel schistosity, i.e. perpendicularly to the Alpine overthrust plane of the Bratislava Nappe, which should moderately merge

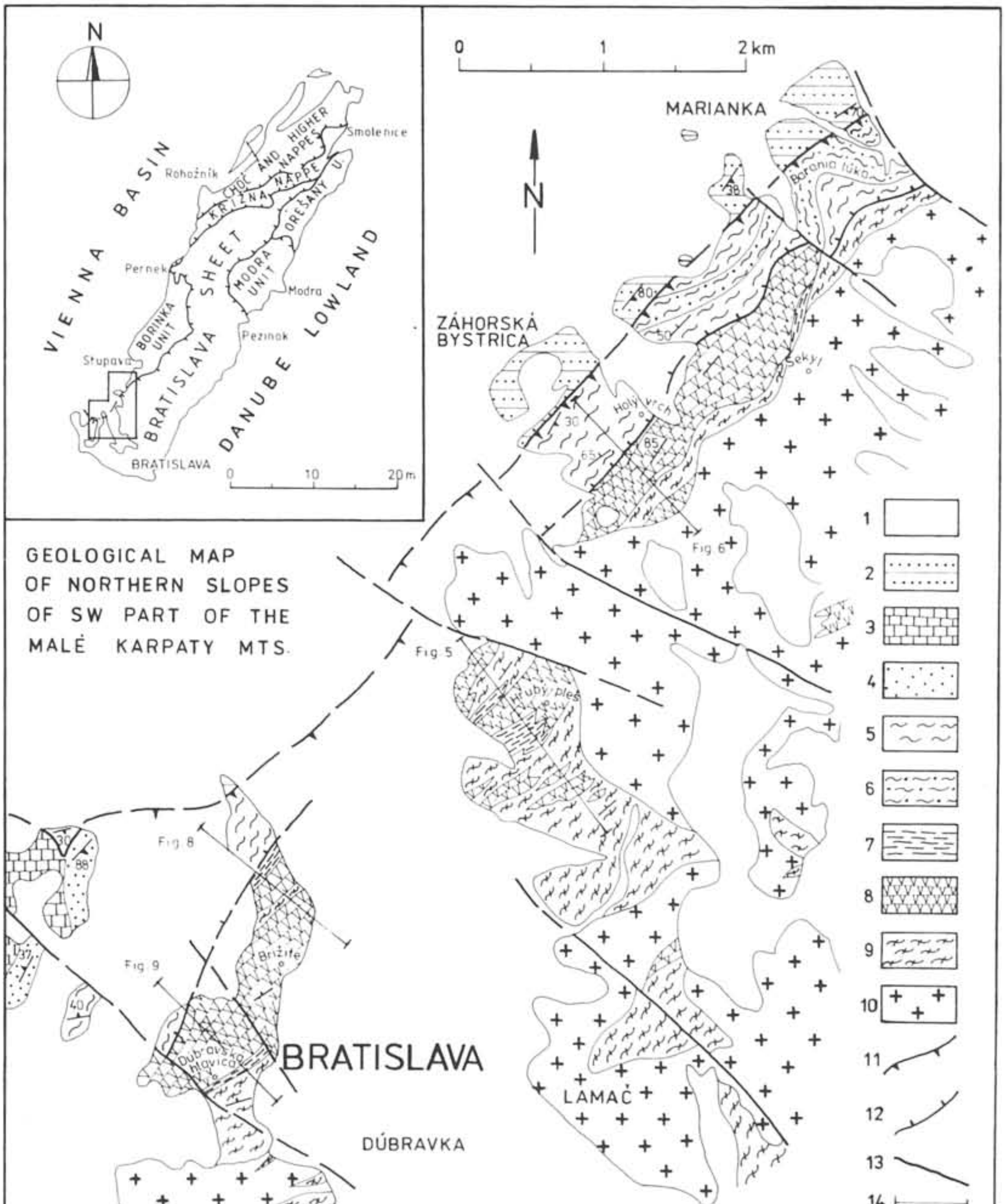


Fig. 1. Geological map of the investigated area.
1 - Cenozoic cover; 2 - Jurassic Borinka Group; 3 - Middle Triasic carbonates; 4 - Lower Triassic quartzites (3 & 4 - Devín succession); 5 - phyllites (metapelites), 6 - metasandstones (5 & 6 - Lower Paleozoic Marianka succession); 7 - black schists to metaquartzites; 8 - amphibolites; 9 - gneisses to mica-schists (7 & 9 - Lower Paleozoic Pezinok succession); 10 - granites to granodiorites of the Bratislava Massif; 11 - Alpine overthrust; 12 - Variscan overthrust; 13 - faults; 14 - profile lines.

towards the SE (Fig. 1). According to a simple extrapolation of surface data, the overthrust plane should cut the amphibolitic bodies at the depth of 200 - 300 *m*. Nevertheless, if adopting a local steeper dip of the overthrust plane in the SE limb of a younger, upright NE - SW trending anticline (Fig. 9),the intersection might be expected at depths of approximately 500 *m*.

The overthrust plane itself is surrounded by a ductile shear zone revealing top-to-NW translation of the Bratislava allochthonous sheet (Plašienka 1989). Ductile strains are confined to a several tens of meters thick shear zone developed mainly in footwall Jurassic sediments (dominantly limestones), while hanging wall basement rocks show ductile-brittle to brittle behaviour during thrusting. Ductile-brittle deformation includes development of shear zone parallel C-foliation overprinting older anizotropies (in metasedimentary rocks) are rarely S-C mylonites in granitoids, brittle tectonites are represented by unfoliated cataclasites and tectonic breccias mainly of competent rocks (quartzites, dolomites, amphibolites, granitoids). The important implication is, that ductile-brittle shearing could produce curving of straight lines of preexisting anizotropies inside the shear zone and hence modify their spatial positions, while brittle crushing could not due to its confinement to sharply bounded lenses (Fig. 9).

Applied interpretation methods

The level of the results obtained strongly depends also on the quality of separation of the anomaly from the map of Bouguer anomalies. It is well known that the anomaly should be caused only by a single disturbing body or at least by anomalous densities of one type linked e.g. with a density boundary so that the interpretation could provide good results (Pick et al. 1973). Moreover, in our case, the gravity effect of both anomalous bodies is mutually affected (see Fig. 2). We have applied the graphic method of separation to solve our problem. The determined residual anomalies are illustrated on Fig. 3a,b,c.

Two mutually independent methods of the three-dimensional inverse problem of gravimetry were used in order to obtain as good results as possible for interpretation. Both results complete each other.

In the first case, the problem was solved by the iterative least square method to interpret three-dimensional gravity fields (Dyrelius 1972). The model used for this aim consists of rectangular prisms. The gravitational effect of irregular masses in any point can be computed in such a way that their shape is approximated by a complex of prisms. The position parameters of the prisms to the points of computation can be changed. This is used to make the model of the anomalous bodies more accurate. This procedure has a good stability and quickly converges if we know at least partly the depths of the upper prism bases while the depths to the lower surfaces are adjusted by the iterative procedure until the best fit is obtained of the whole model (in the least square method) with the input data.

In the second case, the interpretation applied the method of modelling density inhomogeneities at which the gravity effect of the elementary prism is computed based on the relations derived by Talwani & Ewing (1960) and Smíšek et al. (1970). The primary model is made more and more accurate on the basis of the method of gradual minimization of deviations of the computed gravitational effect and the residual, anomaly values.

It follows from the above mentioned that the common "denominator" of both methods is the fact that the anomalous values are being approximated by a geometric body in the shape of a prism and that their solution can have its course with an active participation of the interpreters.

The initial geologic-geophysical models at the same time leaned on geological and geophysical notions of the region being

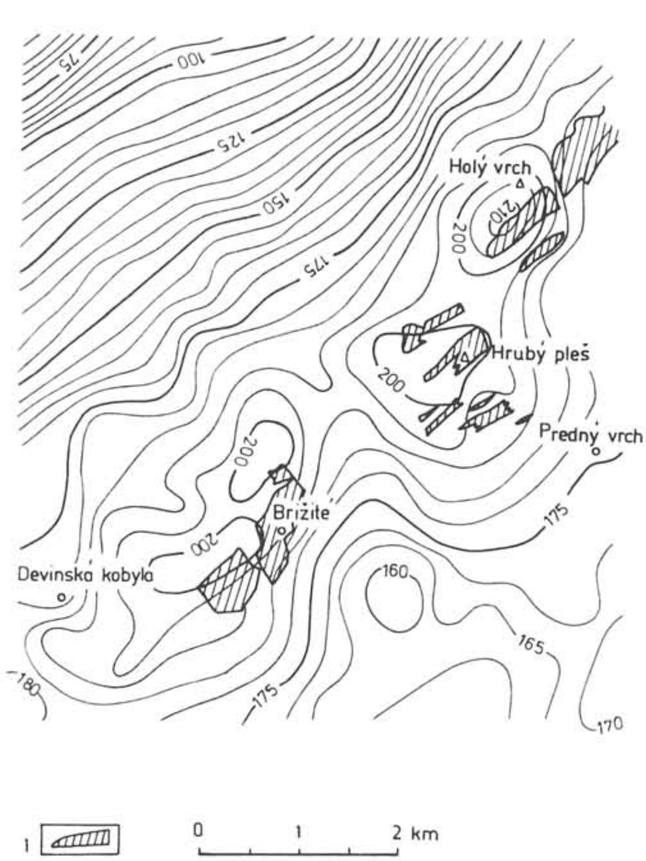


Fig. 2. Map of Bouguer anomalies.
1 - amphibolites on surface.

investigated. It is logical that their accuracy depends on the quality and quantity of these notions. In the iterative least square method, the anomalous matters were approximated only by one prism owing to simplicity. In this case, determination of the lower limitation of the amphibolite bodies was mainly concerned. The differential density of $\Delta\rho$ the anomalous bodies within the interval from 0.15 to 0.20 Mg/m^{-3} was determined based on the analysis of densities of the amphibolite rocks and the rocks located in their environment (Eliáš & Uhmann 1968, Husák in Šefara et al. 1987). The modification of the "starting" models was performed based on changes of the geometric parameters characterizing the anomalous amphibolite bodies. These changes, however, were not arbitrary but were limited just by geoscientific notions. In the first method, the gravity effect was computed in the square network with the step $\Delta x = \Delta y = 0.25$ *km*; in the second one, along the x-axis, the step $\Delta x = 0.1$ *km*. The altitude of the computed level was 280 *m* above sea level in both cases.

In addition we also decided to apply a quantitative interpretation to the third anomaly C (Dúbravská hlavica hill and Brižité ridge). The aim of this decision was to complete our geophysical interpretation on all mafic metavolcanic complexes, which outcrop in the SW part of the mountains.

Results of interpretation

Based on the iterative least square method, the depths of the lower edges of the anomalous bodies were determined (Fig. 4a,b). For the amphibolite body in the locality of Hrubý pleš,

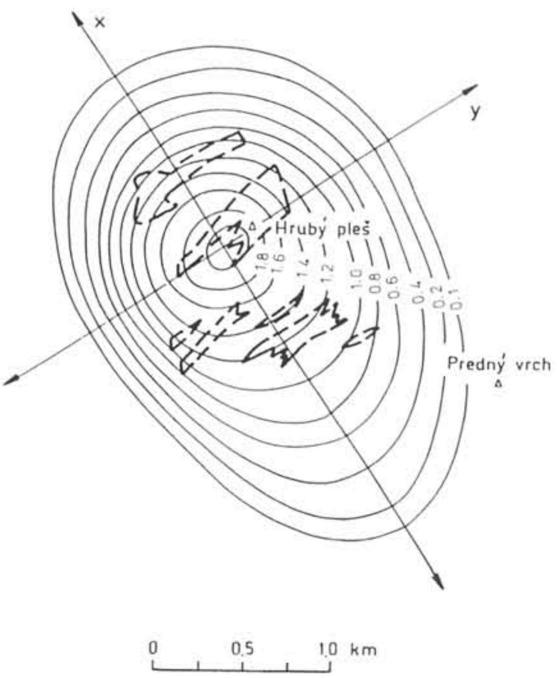


Fig. 3a. Residual gravity map. Locality of the Hrubý pleš.

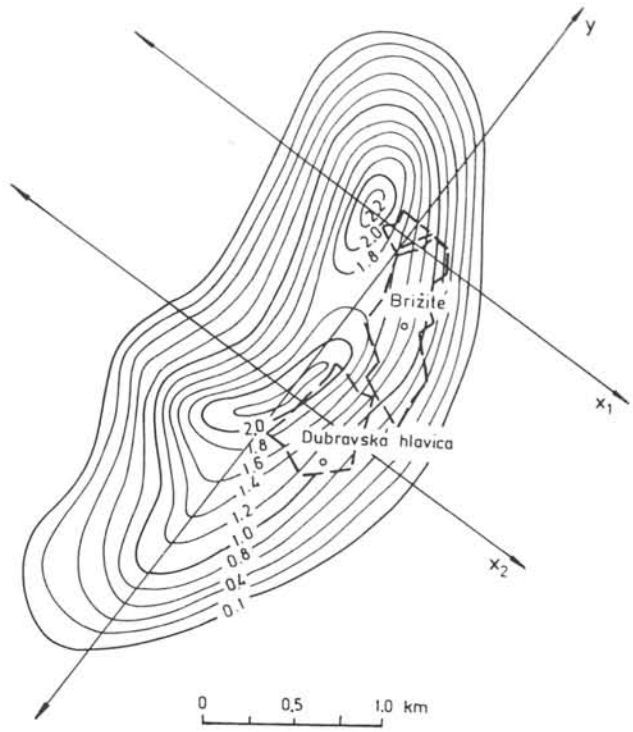


Fig. 3c. Residual gravity map. Localities of the Dúbravská hlavica hill and Brižité ridge.

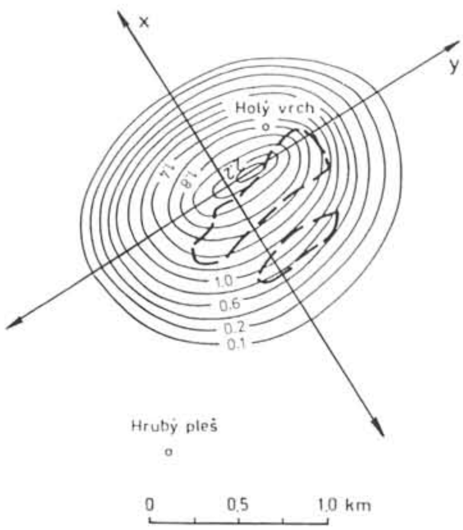


Fig. 3b. Residual gravity map. Locality of the Holý vrch hill.

this parameter equals 309 m at $\Delta\rho = 0.20\ Mg/m^3$, and 475 m at $\Delta\rho = 0.15\ Mg/m^3$, respectively. For the second anomalous body located in the environment of the locality of Holý vrch hill, the average depth of the lower edge was determined to be 750 m at $\Delta\rho = 0.20\ Mg/m^3$, and about 1600 m at $\Delta\rho = 0.15\ Mg/m^3$. These important parameters were used in compiling the "starting" geologic-geophysical models for the second interpretation method. In the case of the anomaly of Hrubý pleš, three initial models were proposed which would characterize the shape of the anomalous amphibolite bodies. It was interesting to note that in applying the method of gradual minimization, all the three models led to the same final result (Fig. 5). The resulting interpretation of the amphibolite body of Holý vrch hill, Dúbravská hlavica and Brižité ridge is illustrated on Figs. 6, 7, 8. The maximal depth of the lower edge of all bodies varies about 400 - 600 m.

Tectonic interpretation

Quantitative 3D modelling of gravity anomalies has achieved interesting results expressed by uniformly crescently shaped source rock bodies in four profiles through a continuous belt of more or less identical geological structure. Profiles are spread for a distance of 5 km, which allows us to exclude a possibility of coincidence and to ascribe obtained figures to real, genetically conditioned tectonic structures.

The conception of large-scale recumbent folding in the frontal parts of the Bratislava basement Nappe has been recently proposed by Plašienka et al. (1989, 1991). The Devín Mesozoic succession forming a paraautochthonous cover of the Bratislava crystalline basement in the SW neighbourhood of the investigated area also creates a macrofold with subhorizontal axial plane. The tightness of the fold strongly depends on the competence contrast of folded rock layers. Upper Permian and Lower Triassic quartzose sandstones, comparable to amphibolites as far as are concerned their thickness and rheological properties under brittle conditions, form an open, shallow macrofold with subvertical bedding attitude. Middle Triassic dolomites also form an open macrofold, but with more tightened outer bend due to a restricted ductile flow in a limestone interlayer squee-

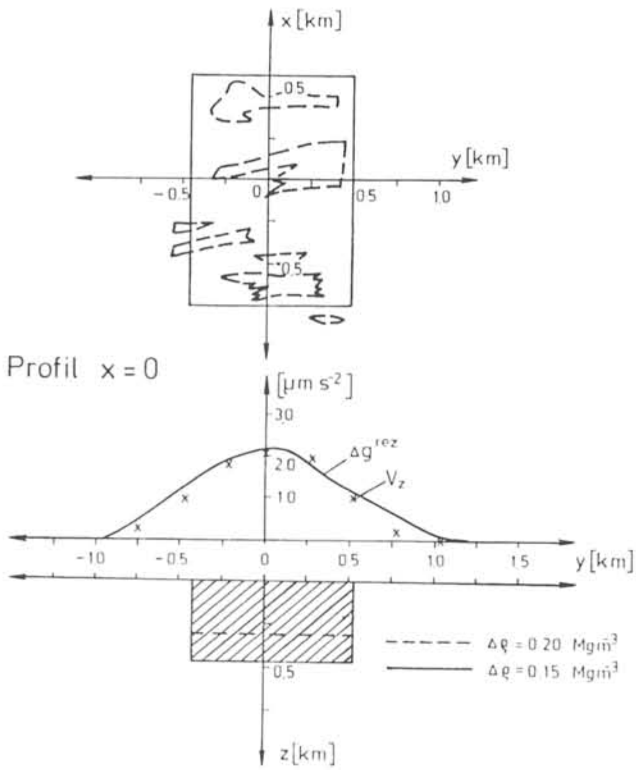


Fig. 4a. Approximation of the anomalous body Hrubý pleš and its vertical cross-section.

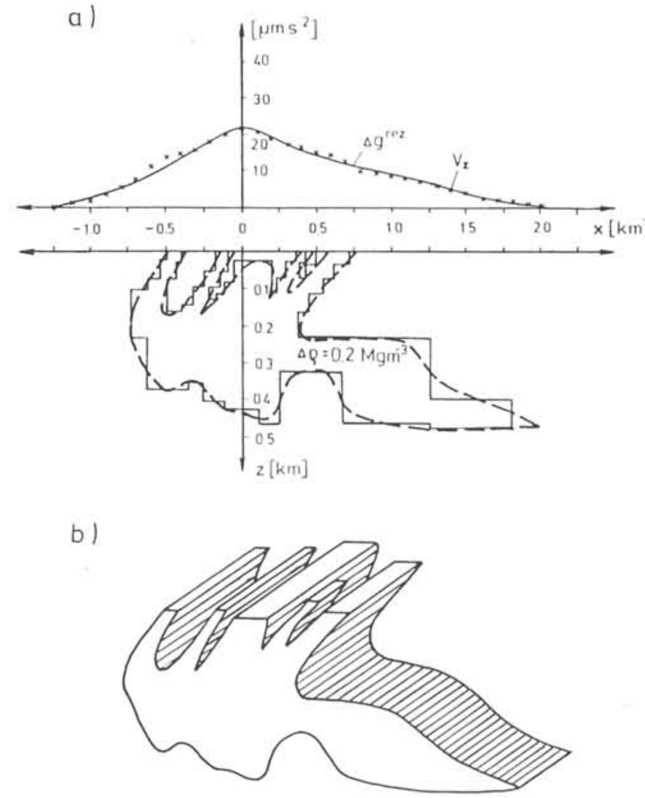


Fig. 5. Vertical cross-section of the best-fit model of the anomalous body Hrubý pleš: a - profile along the axis; b - perspective view of this model.

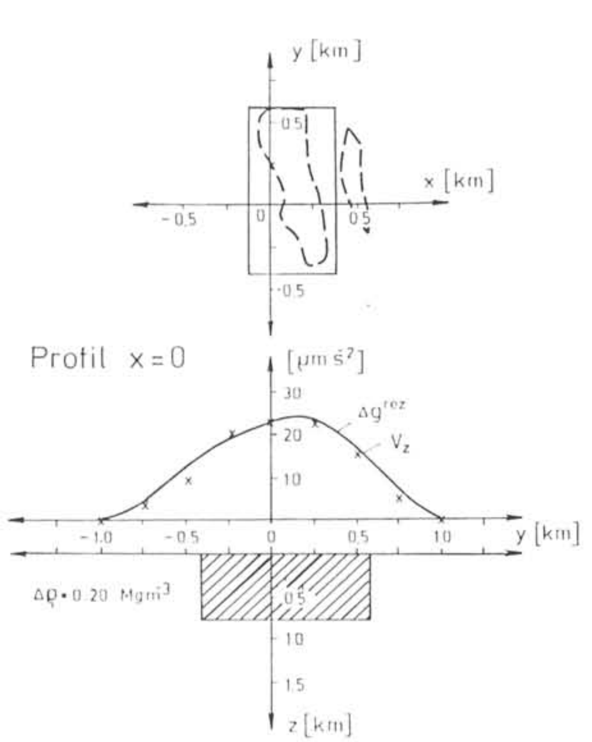


Fig. 4b. Approximation of the anomalous body Holý vrch hill and its vertical cross-section.

zed in the hinge zone (Fig. 9). Upper Jurassic to Lower Cretaceous well-bedded limestones are marked by a tight to isoclinal macrofold with completely preserved overturned limb.

It is worth noting that all rock layers show bending not only below, but also over the axial plane of the recumbent macrofold, therefore fold origin cannot be ascribed only to a simple shear curving in the overthrust shear zone. However, some restricted dragging at the base of overthrust sheet may have contributed to this curving especially in ductilely deformed layered media and may have also caused the appearance of some "tails" of competent layers probably due to a brittle segmentation as can be observed on Figs. 5 and 8.

The restored position of rock succession from Fig. 9 would imply longer lines of upper, less competent strata compared to underlying more competent rock layers. This can be explained simply by heterogeneous deformation throughout the far-travelled overthrust sheet. Nevertheless, we propose a more sophisticated explanation: longer lines of post-Liassic, i.e. post-rift sediments is a primary-sedimentary phenomenon, caused by Early Jurassic rifting and the subsequent extension of observed macrofolds originated from the inversion of pre-orogenic extensional crustal structures (Plašienka et al. 1991). Paleogeographical analysis indicates a deposition of the Devín Mesozoic succession in a halfgraben over a listric normal fault facing SE. Incipient inversion and shortening initiated buckling and cuspate-lobate folding at the competent (basement and pre-rift cover sequence) and incompetent (post-rift sequence) interface. Overstepping of a frontal ramp (previously normal fault escarpment) brought about and allowed rotation of an originally upright macrofold to a recumbent position and facilitated fur-

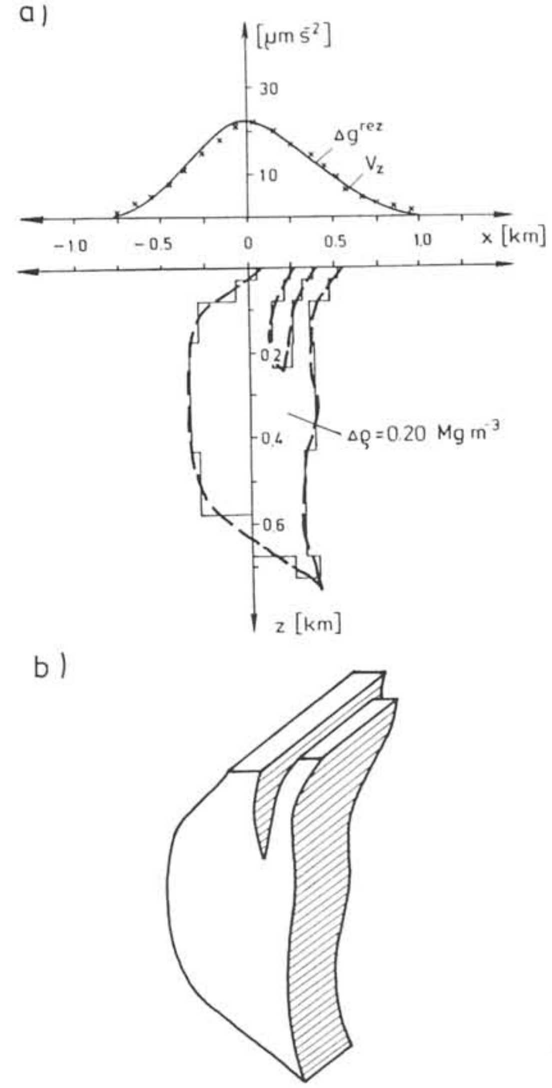


Fig. 6. Vertical cross-section of the best-fit model of the anomalous body Holý vrch hill: a - profile along the X-axis; b - perspective view of this model.

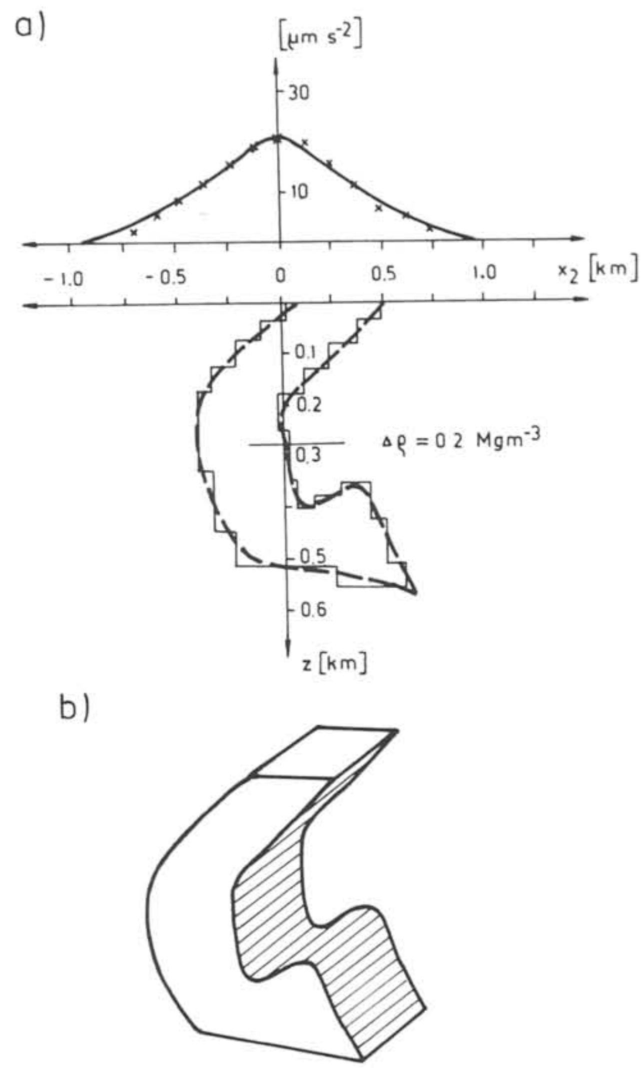
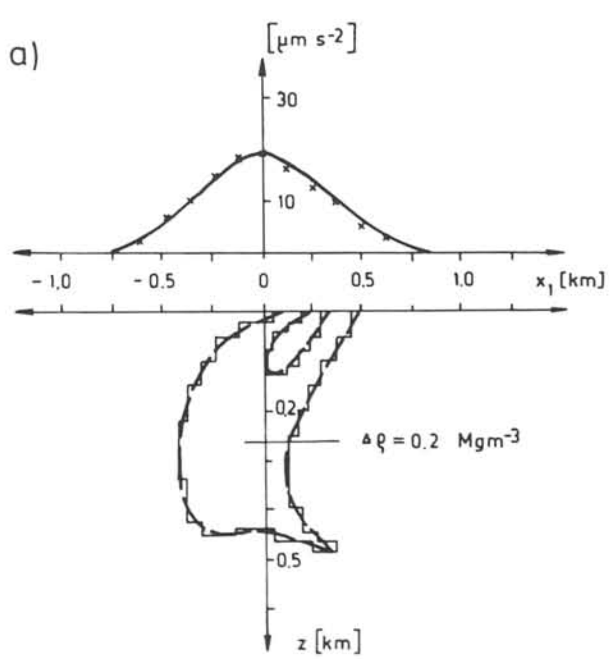


Fig. 7. Vertical cross-section of the best-fit model of the anomalous body Dúbravská hlavica: a - profile along the X_2-axis; b - perspective view of this model.



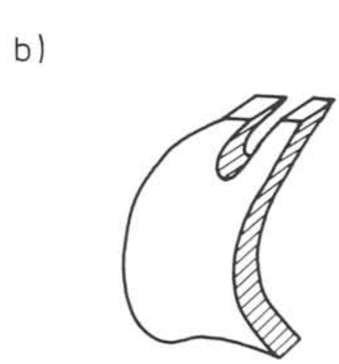


Fig. 8. Vertical cross-section of the best-fit model of the anomalous body Brižité: a - profile along the X_1-axis; b - perspective view of this model.

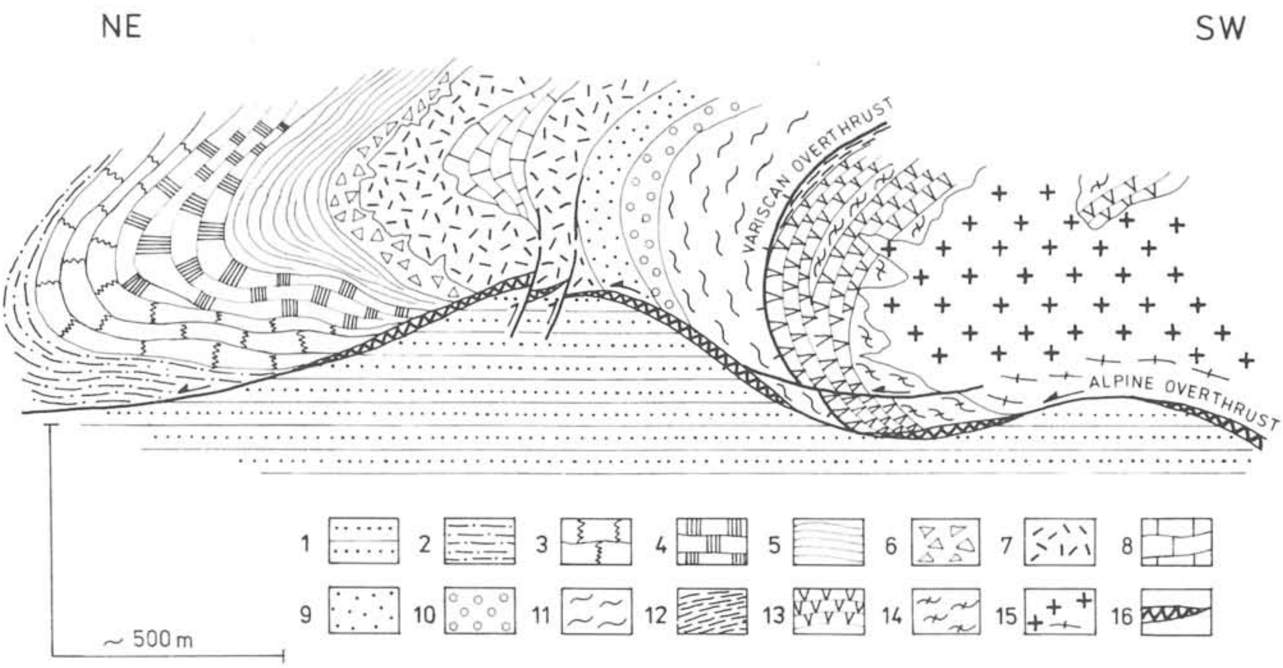


Fig. 9. Integrated schematic cross-section of the macroscopic recumbent anticline in frontal parts of the Bratislava allochthonous sheet. Note the differnce in the tightness of the macrofold between the basement and tegument pre- and syn-rift cover sequence (massive-competent, open curvature) and post-rift sequence (well-bedded, incompetent, isoclinal curvature).

1 - Borinka unit; 2 - Middle Cretaceous flysch; 3 - Neocomian thick-bedded limestones; 4 - Upper Jurassic thin-bedded limestones and silicites; 5 - Middle Jurassic shales; 6 - Lower Jurassic breccia limestones; 7 - Middle Triassic dolomites; 8 - Middle Triassic limestones; 9 - Lower Triassic quartzites; 10 - Permian clastics (2 to 10 - Devín succession); 11 - phyllites; 12 - graphitic schists; 13 - amphibolites; 14 - gneisses; 15 - granitoids; 16 - cataclasites.

ther overthrusting and restricted macrofold tightening through lower limb shearing and flattening. Overstepping was probably attended with a footwall shortcut, the remnants of which are partly preserved as blocks in overthrust tectonic breccias. This mechanism seems to be able to explain the main features of the geometry of the basement and cover bearing recumbent macroscopic folds as well as the strain distribution in the overthrust sheets at least in terrains, where early crustal extension followed by inversion is fairly well documented by a sedimentary rock record.

Conclusion

The interpretation of small local gravity anomalies induced by amphibolites in a metasedimentary-granitic environment has resulted in a set of best-fit models, which show almost uniform crescent shape and comparable depth reach of anomalous bodies. Consequently, we have adopted these results as reliable enough for the tectonic interpretation. Nevertheless, it should be kept in mind that these results are still only preliminary, because shapes and depths of interpreted anomalous bodies are strongly affected by the selected average density contrasts and by the quality of information about the ambient density distribution.

The tectonic interpretation is based on the position of anomalous bodies in the core of a large-scale recumbent anticline developed in the frontal parts of the Bratislava allochthonous thick-skinned sheet. Kinematic reconstruction of the origin of the basement fold assumes firstly cuspate-lobate buckle folding at the basement/cover interface due to an inversion of an extensional Mesozoic basin and secondly external rotation of upright macrofolds into a recumbent position during overstepping of a frontal ramp (originally an extensional normal fault escarpment). Subsequent overthrusting partly tightened the macrofold through restricted flattening and shearing of the lower limb.

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