First results of the gravity modelling along the line 1gm in the North-Eastern part of the West Carpathian Flysch zone in Slovakia

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Abstract. The gravity profile **1gm** in the Eastern Slovakian Flysch zone transects the Pieniny Klippen Belt, Magura and Dukla units. The Klippen Belt forms a narrow tectonic structure at the borderland between the Inner Carpathians and the Outer Flysch zone. The Flysch units are eradicated nappes floating over the extraneous detached blocks of the crust of continental origin (?European).

The model is based on the recent gravity measurements and it is supplied by geophysical and geological data. For calculations we used the reduction density of 2,67 g/cm^3 has been used. The Moho-layer was designed after the Horváth´s (1993) model, with stepless surface dipping to the north. The Inner Carpathian tectonics is based on general geological situation (Biely et al. 2000, resp. Lexa et al. 2001) extrapolated to the depth, using the interpretations of the seismic sections (Vozár et al. 2000).

The Flysch units appear all slightly lighter than „normal„ in our model with density inversion to the depth. This may be geologically explained as an influence of younger (Oligo-Miocene) sediments of the Outer Carpathian nappes under the Magura group of the nappes. To the north of our profile the deep depression was modelled, as the Polish interpretations indicate (Żytko 1999, Królikowski – Stefaniuk 2000).

The magnetometric DT graph along the profile is also presented. It is structured to the three main fields coincides with the surfacial geology and regional characteristics of the gravity field.

Key Words: West Carpathians, Eastern Slovakia, Flysch zone, gravity, density modelling, magnetometry

Introduction

The Slovak territory is covered by gravity measurements already from early seventies. The area of eastern part of the Flysch zone of the West Carpathians was measured with grid density of 3 pt/km^2 (Pospíšil – Hančinová 1974). More precise data were recently gained along the three gravity profiles measured in the north-eastern Slovakia (Fig. 1).

Profile **1gm** is easternmost of the three: it starts in the Vyšný Žipov village, runs to the NE over the river-dam Domaša to Oľka village and ends at the Slovak-Polish state frontier.

Profile **2gm** starts in Kežmarok town, it is directed to the NW and ends in Tatranská Javorina village.

Profile **3gm** is S-N oriented. Southern end bears on the Nízke Tatry Mts., to the north crosses the Liptov depression and terminates in the Račková valley in Vysoké Tatry Mts.

The geophysical measurements in the northern regions of the Slovakia were undertaken to link the data from the territories of surrounding countries.

Geological setting

The region of the Eastern Slovakia along the gravity profile **1gm** and in adjacent Polish territory is build of the West–Carpathian Flysch Zone. Only at the southernmost part the profile hits the Inner Carpathian Paleogene and crosses the Carpathian Klippen belt. To the north, the line transects the Magura nappe and ends in the Dukla unit (see Fig. 2).

Flysch zone within this realm forms structured Magura unit, overthrusted to north-east to Dukla and Silesian unit. The surface units are underlain to the depth with the Obidowa–Slopnice unit. This is lately considered by some Polish geologists to be an equivalent (if not identical) to the Dukla, or the Silesian unit respectively (e.g. Burtan et al. 1992, Cieszkowski et al. 1985). The extension of the Obidowa – Slopnice unit was proved by the boreholes, e.g. Obidowa IG-1 (Cieszkowski 1986, Cieszkowski et al. 1985), Zborov-1 (Koráb et al. 1991) or Zboj-1 (Koráb, Ďurkovič 1980, Ďurkovič, Koráb et al. 1982).

All the three tectonic units (Dukla, Silesian and Obidowa-Slopnice) belong to the Middle Group of the nappes, sometimes referred together with the External units simply as „the Krosno Flysch", while the Magura unit forms the Inner Group of nappes (after Nowak 1929, also Kśiaźkiewicz 1972).

Structurally, the nappes are overthrusted and stacked with north-eastern vergency one over another, from the innermost (as the highest) to outer (the lowest). Altogether, the nappes are overthrusted to the European platform.

Inner structure of the Magura unit is extremely complicated. The division to the three tectonic-facial units applied to the western part of the Flysch zone is only

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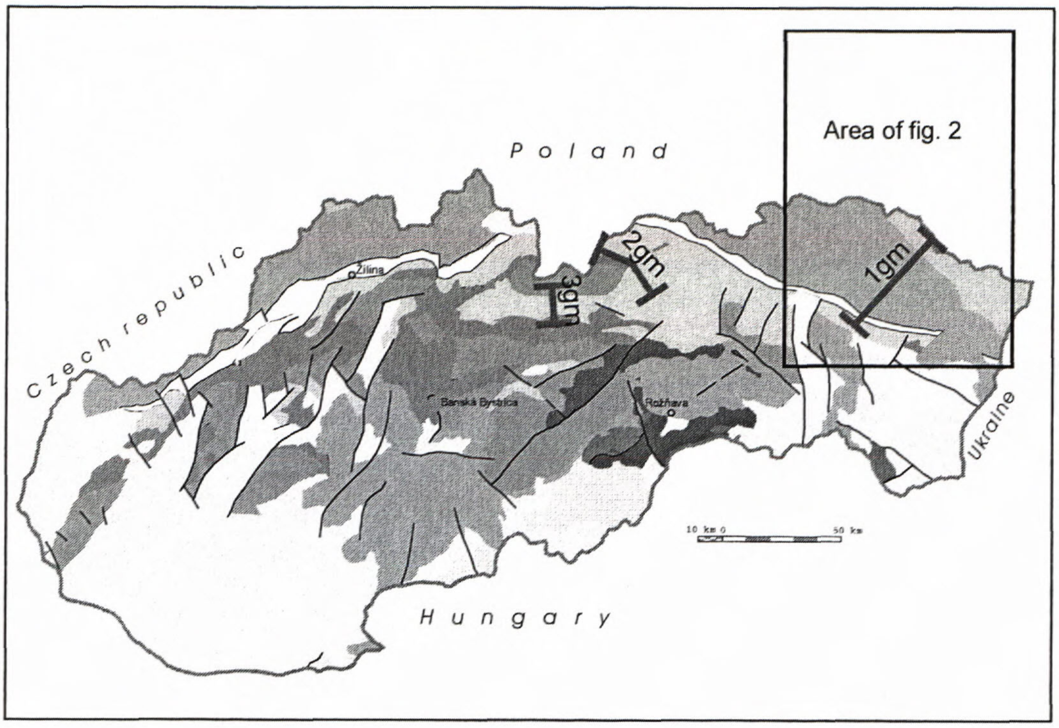

Fig. 1 Location scheme of the gravity profiles and the study area.

roughly applicable to the area between Čergov Mts. and Ondavské vrchy Hills. This is due to the absence of the recent detailed maps and due to the less pronounced structural zones. The innermost zone of the Magura nappe – the Krynica unit is built mainly of the Paleocene-Eocene sandy flysch with massive sandstones grouped in the Krynica, Poprad or Strihovce beds. They are underlain by Beloveža beds (Lexa et al. 2000).

The Bystrica and Rača units consist of typical Paleocene to Eocene flysch of the Beloveža beds followed by the Zlín formation. We do not know such large extent of the Cretaceous sequences (Soláň or Inoceramian beds) in the East Slovak territory, as they outcrop in Poland (Lexa et al. 2001).

The stratigraphic column of the Magura is terminated by Oligocene Malcov formation. This consists of less consolidated sandstones, sandy clays and siltstones.

The Dukla unit is built of complete sequence from Cretaceous Lupkov and Cisna beds, through Submenilite and Menilite beds to the Oligocene Krosno and Cergowa beds (Ślączka 1971, Koráb, Ďurkovič 1978).

A special stratigraphy was determined for the Obidowa–Slopnice unit (Cieszkowski 1986, Jawor, Sikora 1979) containing flysch lithology, with „black Eocene„ characterized with horizons of sedimentary slump breccias.

Detailed study and interpretation in early nineties by Koráb et al. (1991) revealed very complicated scaly structure of the Magura partial units, with unexplained position of the Smilno tectonic window (Dukla unit?) in direct position over the Obidowa–Slopnice unit.

The Outer flysch units (e.g. Skole nappe) contain the sedimentary sequences from Cretaceous (Spas and Stryj beds) to Oligocene (Menilite and Krosno formations) (cf. Lexa et al. 2000). These are stacked internally and one over another in detailed scaly tectonics, originated in the Late Miocene.

Top of the European platform under the flysch nappes is well traced by the deep drillings and it is also recognizable in seismic lines roughly as far as the surface line Jaslo – Kuźmina, where we lose direct information about the platform surface (Wdowiarz 1976) (EPR-line in the Fig. 2). Further continuation of the platform to the south is inferred from geophysical data, such as distribution of the gravity field, character of the high resistivity basement and extent of the high conductivity layer (Żytko 1997, 1999). Thus stated platform may be interpreted roughly to the surface line Dukla – Lupkow, or to the Slovak–Polish borderland (Żytko l.c., Roure et al. 1993).

The platform under the Flysch nappes consists of the crystalline basement (Żytko 1997, 1999) covered by Paleozoic and Mesozoic sedimentary mantle south of the Rzeszów. To the NE pre-Tertiary sedimentary cover is eroded (Oszczypko et al. 1989). A younger – Neogene molassic autochthonous sediments cover the most of the platform area in the NE prolongation of our gravity profile (e.g. Czepiec, Kotarba 1998). These consist of faintly consolidated molassic and deltaic sands, conglomerates and clays and submarine fan deposits (Karnkowski 1977, Jucha 1985, Ślączka et al. 1986, Oszczypko, Ślączka 1989, Kotlarczyk 1988).

Several attempts were made to restore the original size of the flysch basins, especially their width (i. e. the course across the basin, here NE-SW) (Roure et al. 1993, Oszczypko – Ślączka 1985, Roca et al. 1995). The method of balanced sections furnishes an estimation of more than 50 % shortening of the flysch basins during the Neogene. Thus if we deploy the pile of the flysch nappes and sheets, the present southern rim of the Magura would lain at least 250 km to the SW (cf. also Potfaj 1998).

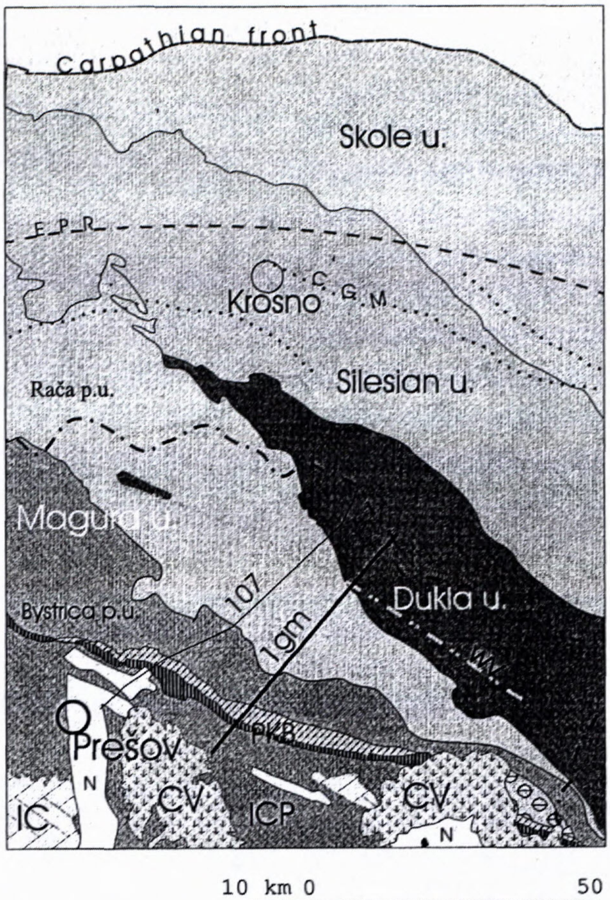

Fig. 2 Geological and geophysical features of surroundings of the gravity profile ***1gm****.*
Explanations: EPR – southern rim of the proven European platform, CGM – Carpathian gravity minimum, wv – zero value of the Wiese vectors, PKB – Pieniny Klippen Belt, ICP – Inner Carpathian Paleogene, IC – Pre-Tertiary elements of the Inner Carpathians, CV – Tertiary volcanics (in green), N – neogene sediments (in yellow). 1gm – location of the gravity profile, 107 – location of the seismic reflection line

The common problems of all reconstructions are interpretations of the substratum of Magura nappe and then the character of more than 12 km deep depression under Magura – Dukla realm. To this region we miss relevant seismic data, as the internal structure of the Magura and related lower units are intensively folded and faulted and as such they do not reflect interpretable seismic waves. This NW-SE directed zone coincides with several distinguished geophysical features: West-Carpathian gravity depression, zone of high conductivity, zone of the inversion of the Wiese´s vectors (wv-line in Fig. 2).

The Klippen Belt

This phenomenal West Carpathian narrow structure borders at the surface the Flysch zone from the south. It is tectonic zone composed of Jurassic – Lower Cretaceous carbonate hard rocks torn to blocks and pieces seated in the plastic Late Cretaceous to Paleocene marls (Púchov, Macelowa, Gbelany – generally „couches-rouges„), clays and flysches (Jarmuta, Proč and Snežnica beds).

Hanušovce 1, Maruszyna IG1 and Szaflary PD 9 boreholes proved nearly vertical course of the Klippen structure down to 5-6 km (Leško et al. 1985, Chowaniec, Sokolowski 1986, Birkenmajer et al. 1979). From the north the Klippen Belt is bordered by narrow zone of the Proč beds (quartz-carbonate sandstones, marls and claystones), which we include structurally as well to the Klippen zone. This sequence emerges all along the Klippen Belt from Váh valley to Vihorlat-Gutin Mts. on Ukraine. It belongs to the „Klippen Belt Paleogene". We may correlate this sequence with the one from the Biele Karpaty unit in the Western Slovakia (Potfaj 1993, Stráník 1989).

Along the Klippen belt there are associated some small tectosomes (tectonically formed and confined bodies) of Tertiary stratigraphic elements, such as Malcov beds in Orava (Potfaj 1983) or Neogene at Nowy Sącz (Paul, Poprawa 1992). Some of such bodies we suppose also in the sector of our profile.

Inner Carpathians

We use this term in the sense of the Roth´s (1980) definition, marking as Inner Carpathians the realm „inside„ the Klippen Belt. The Inner Carpathian nappe structure was completed in pre-Turonian, in contrast to the Outer (= Flysch) West Carpathians, where the nappe structure is Neo-Alpine, i.e. post Senonian (see Biely et al. 1999). Over the Inner Carpathian nappe structure the Paleogene sea was spreaded. The transgressive sediments at the base are of Middle to Late Eocene age, followed by more or less flysch-facies of Huty, Zuberec and Biely Potok formations. In our region only reduced stratigraphic column occurs.

The Neogene sands and clays fill the East Slovakian basin, which is tectonically confined to the west from the Mesozoic and Paleozoic central Carpathian units. These belong to Veporic and Gemeric (both tectonically separated) and further to the south (south of the Darnó fault zone), we may expect also the Mesozoic units of the innermost part of the Western Carpathians, as an equivalent of the South Alpine – Dinaric units.

The confinement of the units is mostly tectonic, with vertical faults, of which some may have acted as strike-slip shifts. The tectonic relations are proved also by reflection seismic profiling (Vozár et al. 2000, Mořkovský 1981).

Geophysical features

Several seismic profiles were shot in the region of the Eastern Slovakia, the quality of gained data is various due to the loss of the signal in the tectonised flysch medium. Late interpretation of the selected profiles was published by Vozár et al. (2000).

a) Seismic cross-section 107/88 - 107/89

The profile runs just 5 km west, parallel to our profile **1gm** (Fig. 2). It begins in the SE part of the Laborec Hills in the Dukla Unit of the Krosno Flysch and it passes to-

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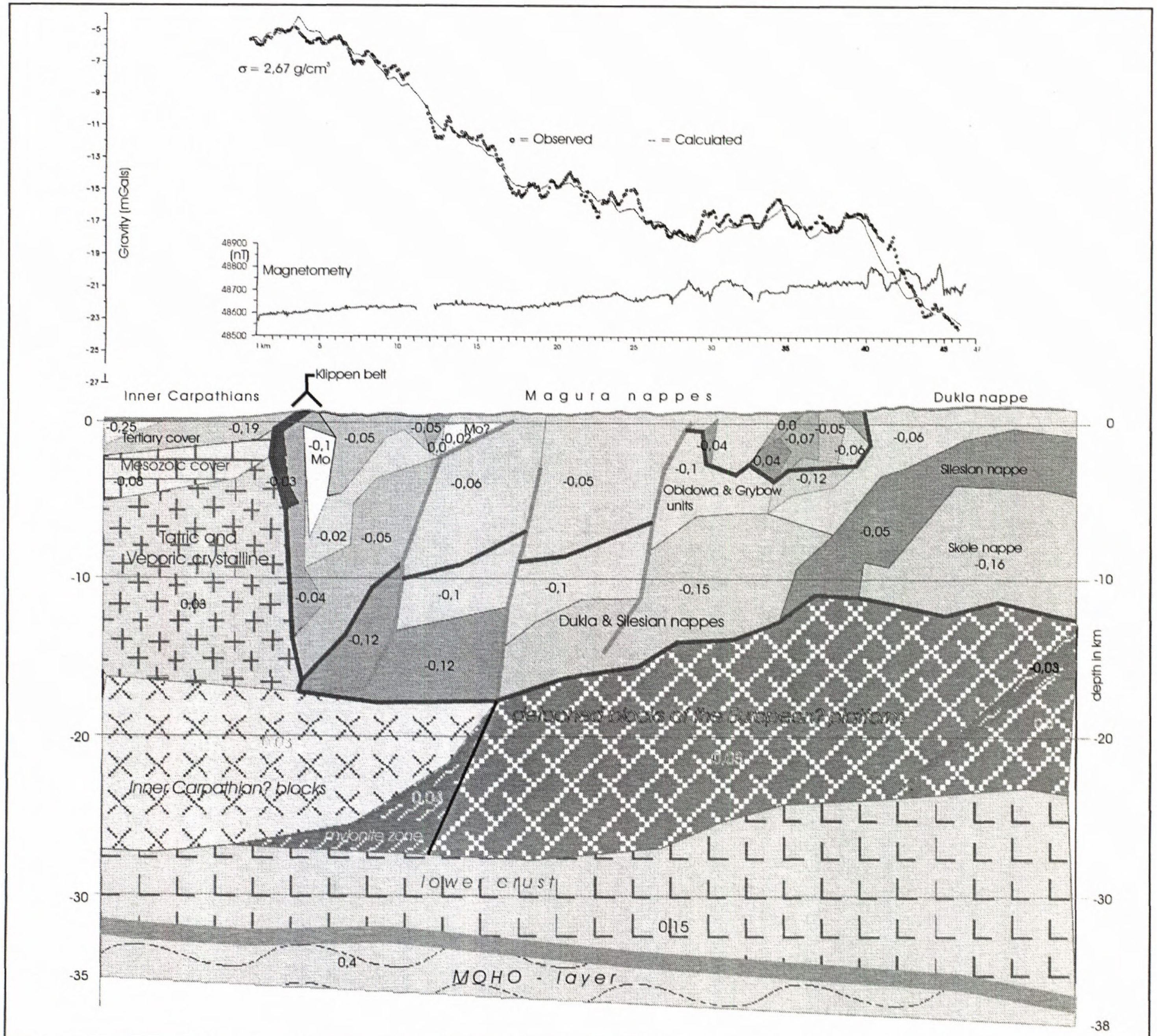

Fig. 3 Geophysical – geological cross section along the line ***1gm***.
Explanations: In the density model the numbers denote differential densities of individual bodies in g/cm³
Mo – Oligo-Miocene sediments

ward NW across all Magura partial units (see Vozár et al. 2000). The confinement of main flysch units is tectonic and they are manifested by conspicuous reflectivity. A strong reflector at 18 - 20 km may represent a steep thrusting of Bystrica unit on the Rača unit within the Magura Flysch. The reflectors of the inner structural arrangement of the Magura unit as well as thrusting of the Magura unit onto the Krosno unit are not distinguishable.

Shallow reflections at the southern end of the profile are from the Tertiary sedimentary sequences, and their Mesozoic basement (Humenné unit).

Steeply inclined short reflections in the vicinity of the Klippen belt may be interpreted as intensively deformed zone along the Klippen belt. Low energy of the signal does not allow to view the continuation of this zone into the depth, to prove the existence of the Peripieniny lineament (Sikora 1976). Inclined reflections beneath the 15th kilometer dipping toward S and N may reflect internal structure of the Pieniny Klippen Belt.

Further toward NE in the whole crust reflectors dip toward the south. The MOHO discontinuity is only faintly observable forming the channel of longer disconnected reflections, gradually deepening from south to the north. Neither from this profile nor from the data of seismic profile 80/87 (to the NW) it is possible to provide continuation of the European Platform from the north.

b) Regional gravity features

Interpreted profile is situated on the slope of the regional gravity field between the Carpathian gravity minimum in the north and the regional positive anomaly in the Transcarpathian basin (Szalaiová et al. in Vozár et al. 1999, Królikowski – Petecki 1995). The axis of the Carpathian gravity minimum runs in the Polish territory along the line Krosno–Sanok–Ustrzyky Dolne (CGM-line in Fig. 2).

The origin of the regional gravity anomalies is derived mainly from the deep seated sources. Only the part of Carpathian gravity minimum is explained as originated from the lighter sedimentary rocks of the Flysch zone and/or Miocene molassic sediments under the flysch overthrust as stated by Tomek et al. (1979).

A strong gravity gradient on the Polish - Slovak borderline resp. between the Outer flysch units and the Inner Carpathians is caused by the structures in the upper „étage„. The relative gravity maximum on the slope is originated from the buried structures equivalent to the Smilno window. Some diagonal structures occur to the west of the profile.

c) Magnetics

Apart the historical aeromagnetic measurements (Mašín, Jelen 1963) which were not exact enough we dispose with the DT curve along the line **1gm** (Fig. 3). This is the only relevant information about the magnetic field of the concerned region. The local anomalies located mostly over the frontal part of the Magura nappe could be bound to the Fe-oxides enriched sequences. Three wide-wave regional anomalies we may interpret as the basic regional magnetic structures, which could have the origin probably in the base of the Flysch „étage„. The relative minima of the DT curve we ascribe to the existence of tectonic zones where loss of the magnetic susceptibility due to the thermal and stress deterioration of the magnetic properties of the rocks can be expected.

d) Zone of the 0 – Wiese vectors

It is supposed that this phenomenon is joined with low resistivity layer in the depth of 15-20 km under the surface (Źytko 1997, Doktór et al. 1990). The cause of low resistivity is explained as existence of porous medium (sediment or tectonized zone) filled with mineralized (salt) water (Woznicki 1985, Kuśmierek, Ney 1988), or graphitic layer (impregnation) originated from Carboniferous coal (Źytko 1997), or metamorphosed hydrocarbon fluids (Pěčová et al. 1979). The change of the polarity of Wiese´s vectors indicates the deepest part of this zone. The dividing line runs from the west under the Magura unit, and surface projection passes to the Dukla unit crossing at the profile **1gm** line (wv-line in Fig. 2).

Methodology and results of the measurements

The gravimetric profiling measurements were made by the means of the gravity meter CG-3. The station distance on the profile was 80 m. The topographic elevations were determined by technical leveling. The calculation of the Bouger anomaly curve to 2,67 g/cm^3 reduction density was carried out according to the methodology generally used for Carpathian Geodata Project, used by all the engaged countries that practice the field measurements. Besides the gravity measurements the geomagnetic measurements have been also performed at the step of 40 m. The selected sites along the profile were subjected to vertical electric sounding observations.

The measured data along the profile **1gm** has been compared with the originally defined gravity field of the Pospíšil and Hančinová (1974). From this comparison it appears that in contrast to regional and apparently smooth decline of older Bouger curve our presented curve is refined and enriched of high frequency anomalies with detailed structure. Possible sources of these local anomalies lie in the geological structures, which was verified during the processing by Nettleton´s method. It was proved, that fundamental portion of the gravity anomaly in our profile is independent on the topographic relief and the best reduction density was stated to 2,62 – 2,64 g/cm^3. So the reduction density of 2,67 g/cm^3 used in our model is not far from optimal value and it is fully justified.

Interpretation of the gravity data and the model

The quantitative modelling was made on GM.sys software. New gravity measuring along the profile **1gm** (Fig. 3), as well as older data for the prolonged ends of the profile to the south (Szalaiová in Vozár 1999) as to the NE (Królikowski – Petecki 1995) was utilized. The reduction density was set to the 2,67 g/cm^3.

The basic structuring of the gravity profile in the vertical scale is as follows: The upper mantle, the lower crust and the upper crust. We have placed the Moho – discontinuity at the depth of some 25 km in the south, with a dip to the north down to the 40 km. Our model is based on the data completed by Horváth (1993) and Lenkey (1999) for the Carpatho–Pannonian region.

Some older interpretations based on the refraction-seismic measuring indicated the sharp step at the course of the Pieniny Klippen belt, where the Moho–surface falls to depth more than 40 km (Beránek, Zounková 1979, Fusán et al. 1981). After others, the step of Moho-layer is further to the south (Majcin et al. 1988). None of these models were later satisfactorily confirmed.

For the northern overlap of the profile, we accepted Polish data of the European platform surface, as they were presented in several papers (Żytko 1997, Oszczypko et al. 1989). We have confronted our results also with the interpretation of the profile Nr. 16 (Radoszyce, Przemyśl) (Wójcicki, Stefaniuk 2000).

We accepted the astenosphere – lithosphere interface as it was stated by Horváth (1993) and Lenkey (1999). General sinking of this surface from 80 km at south to 130-140 km at the north was also confirmed by several measurements of the magnetotelluric sounding along the profile from Poland, across the Slovakia to Hungary (Ádám et al. 1997).

The structure of the Outer Carpathian nappes is based mainly on the surfacial geological data (geological map of Lexa et al. 2000), on the many detailed studies (e.g. Koráb et al. 1991, Wdowiarz 1976) and results of the boreholes (Żytko et al. 1989). Modelled elements were formed and confined according to the known geological structures at surface and extrapolated to the depth. The density of the individual bodies was set after exact data of Ondra – Hanák 1989.

As a next step, we tentatively changed the density parameters or/and modified local shape of bodies to obtain the best fit of the curve. For an example, to compensate narrow positive anomaly above the Klippen belt we inserted a slice of lighter sediments (Oligocene Malcov beds and/or Neogene sands and clays?) vertically stacked on the northern confinement of the Proč flysch (Klippen belt s.l.).

Discussion

The deep structure of the contact of Carpathians with their foreland is reflected in the geophysical fields. Especially enigmatic is the discontinuity of Moho as marked by Beránek – Zounková 1979, versus Tomek et al. 1989). The Beránek´s interpretations of DSS measurements emphasize velocity characteristics in the horizontal direction (refraction wave). On the other hand, the method of CDP yields generally the vertical direction velocities. Thus, we may expect that the anisotropic structures in the deep may furnish different apparent values. We may imagine the anisotropic layered medium in vertical position, where the record of the first refracted wave (DSS) will behave different, in comparison to refraction seismics (CDP). The gravity modelling is independent of the media anisotropy and eliminates such misinterpretations.

Conclusion

The interpreted gravity profile **1gm** in the East Slovakia is one of the three in this area. It is in southern prolongation of the Polish magnetotelluric cross–section Nr. 16 (Stefaniuk, Klityński 2000). As such, it is of high importance as it crosses the enigmatic zone of the Wiese´s zero vector line, and it passes on its southern end through the Klippen belt to the Inner Carpathians. We present here a geological interpretation of the first gravity model along measured line. From the chosen model the gravity inversion implies to depth – Magura sediments are denser than masses of the lower, Obidowa, Dukla and Krosno units. The Moho – layer is inclined to the north, being thus the general cause of the north dipping gravity gradient.

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