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Magnetic field of the Western Carpathians (Slovakia): reflections on the structure of the crust

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Abstract: A new digital magnetic map of Slovakia on the scale of 1 : 200,000 and 1 : 500,000 was compiled at the end of 2008 as the output of database magnetic objects from the whole territory of Slovakia at a scale of 1 : 50,000. The variable geological structure of the West Carpathian crust is depicted in the equally variable magnetic field of this region. A sizable number of magnetic anomalies with manifold character have been recognized. The basic anomalies distribution was divided into two groups: anomalies connected with rocks of the pre-Neogene basement and anomalies which originate in Neogene and Quaternary volcanic products. Most of the significant anomalies in the pre-Neogene basement were interpreted, modelled and consequently its geological and tectonic classification was worked out. On the basis of the anomalous field features, the following sources of anomalies have been distinguished: a) known, located on the surface, or at shallow depths verified by boreholes, mainly expressed by simple morphology, b) deep-seated and expressed by complicated morphology, reinterpreted or newly interpreted and also problematic. According to our present knowledge the interpretations are insufficient and remain open for further investigation. The above mentioned sources of magnetic anomalies are classified in terms of tectonic provenience to the main tectonic units.

Key words: Slovakia, magnetic field, magnetic map, geological and tectonic interpretation.

Introduction

The Western Carpathians are characterized by a complicated, fragmented crustal structure which was formed during the Hercynian, Paleo- and Neo-Alpine orogenic stages. This inhomogeneity of the crustal structure is the main source of complicated features of the magnetic field (Fig. 1). Recent works from geology (Fusán et al. 1987; Biely et al. 1996; Plašienka et al. 1997; Bezák et al. 2008) and geophysics (Bielik 1995, 1998; Vozár et al. 1999, 2003; Kubeš et al. 2001; Bielik et al. 2006), are helpful for explanation of the deep sources of magnetic anomalies in the new magnetic map of Slovakia (Kubeš et al. 2008).

The beginning of regional geomagnetic measurements within the area of the Slovak Republic is dated to the end of the 1950s and beginning of the 1960s. The first results were obtained by measuring the vertical component of the magnetic field in the Východoslovenská nížina Lowland (Man 1961) and in the Podunajská nížina Lowland (Man 1962). A synoptic airborne mapping of former Czechoslovakia (the scale 1 : 200,000, magnetic and radiometric measurements, 2 km flight-line spacing, permalloy detector) was carried out almost at the same time (1957–1960). In the framework of the above-mentioned mapping, the area of Slovakia was measured, though without regions where the Neogene volcanic rocks are found. These were omitted with the remark "heavily disturbed magnetic field". The results of this mapping are contained in the pack of the aeromagnetic maps 1 : 200,000 (Mašín 1963).

A systematic detailed airborne mapping of the Slovak Republic 1 : 25,000 (250 m flight-line spacing; 1 second sampling frequency) was initiated in 1974, with simultaneous application of the airborne proton magnetometry and gamma-ray spectrometry. The all crystalline cores were covered by this mapping to the end of 1983 (Malé Karpaty Mts, Považský Inovec Mts, Tribeč Mts, Strážovské vrchy Hills, Malá Fatra Mts, Slovenské Rudohorie Mts, Branisko and Čierna hora Mts) including interjacent depressions. These measurements also included the all Neogene volcanic mountains (Central Slovak area, Slanské vrchy Mts and Vihorlat Mts) as well as parts of the Inner Carpathian Paleogene (Skorušinské vrchy Hills, Chočské vrchy Hills, Šarišská vrchovina Highlands) and the basins situated in the South of Slovakia (Lučenecká kotlina, Rimavská kotlina and Košická kotlina basins). A significant part of the Levočské vrchy Hills was covered in the years 1991–1992. This technology was applied to a total area of 26,160 km^2 (Gnojek & Janák 1986).

The high quality results from the areal measurements of the vertical (Z) component in the Východoslovenská nížina Lowland and Podunajská nížina Lowland have been recalculated in ΔT (the total vector of the magnetic field) and incorporated into the data set from the airborne proton magnetometry. This produced a database of ΔT anomalies covering about 70 % of the territory of Slovakia. Many of the registered anomalies have been interpreted by Gnojek in Vozár et al. (1999).

The rest of the territory mainly the high-elevation areas (Veľká Fatra Mts, Vysoké Tatry Mts, Nízke Tatry Mts) and the Flysch of the Eastern part of Slovakia were measured by

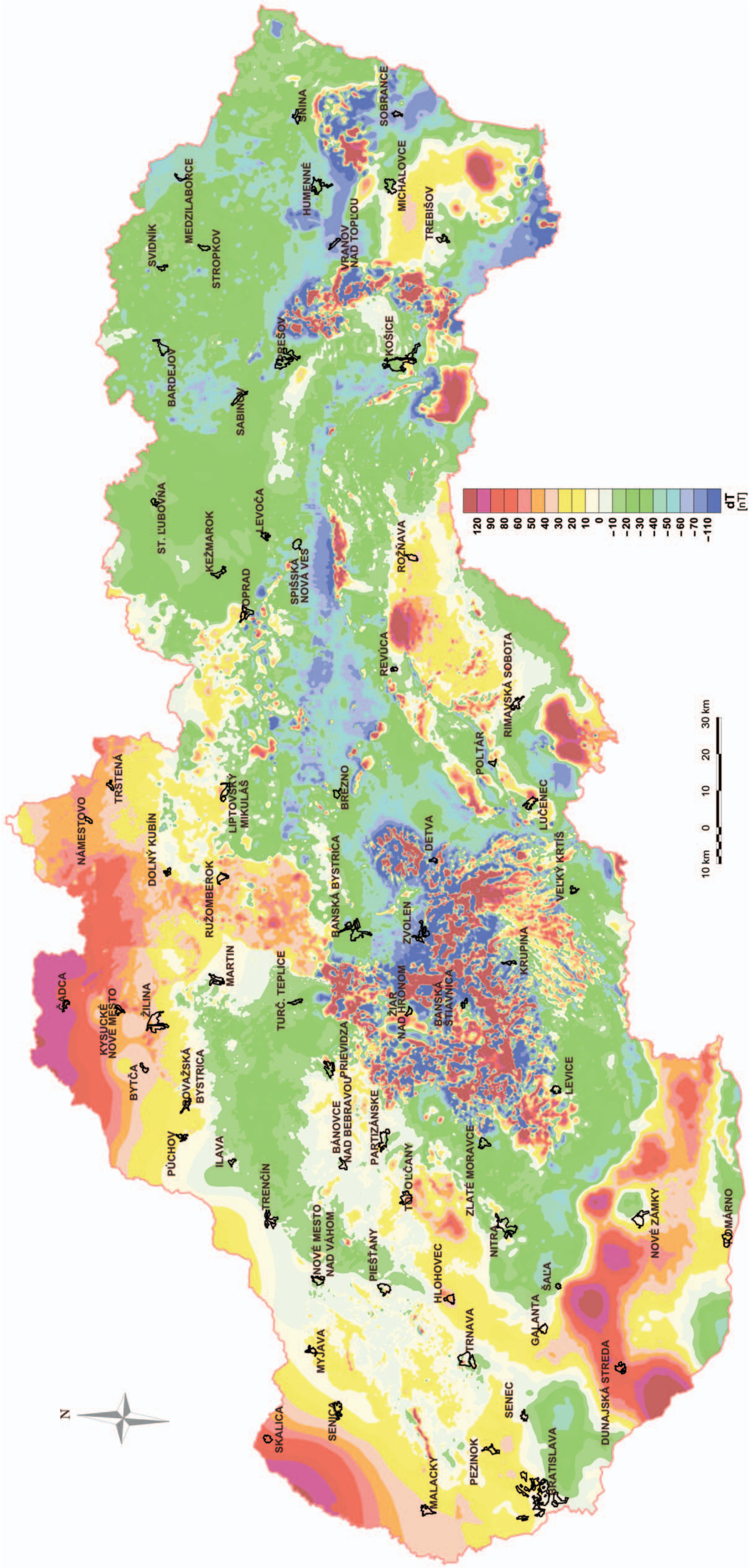

Fig. 1. Magnetic map of Slovakia (Kubeš et al. 2008).

ground application of the proton magnetometry with the density of 1–3 points/km^2 (Kubeš et al. 2008). This produced a comprehensive database of magnetic anomalies ΔT, which is the basis for the new magnetic map of the Slovak Republic.

Methodology

Many anomalies recognized by airborne measurements have been verified by the ground survey. The interpretation of younger magnetic rocks (Neogene and Quaternary) is further complicated by the abundance of normal and reverse magnetic polarization. All the measurements were reduced to the normal magnetic field (IGRF 1995 — International Geomagnetic Reference Field).

The density of the measurements is sufficient for construction of a map with a scale of 1:50,000. Every difference in the magnetic field above 15 nT can be considered as anomalous and should be explained by a geological reason. Most of the measured magnetic anomalies were interpreted in detail in separate publications (Kubeš et al. 2002; Filo et al. 2003; Bezák et al. 2004b; Kubeš & Kucharič 2005).

The interpretations of subsurface anomalies in this work are almost without changes, but some new possibilities of interpretation are indicated in the group of deep seated sources of anomalies. A classification of anomaly sources has been done in concordance with a new Tectonic map of the Slovak Republic (Bezák et al. 2004a).

The newest investigation utilizing the magnetic database (Kubeš et al. 2001) was carried out by Rozimant et al. (2009) in which the relation between Curie point and the depth of the magnetic crust in Slovakia was studied.

Modelling of the anomaly sources was done by the methodology of Talwani & Heirtzler (1964) and geophysical software Oasis Montaj.

The interpretation of the thickness of volcanic complexes is based on geological knowledge about the horizontal and subhorizontal bedding of lower margin magnetic active rocks deposited on environments with non-magnetic or slightly magnetic content. The relation between geological objects, relief of the field and magnetic field changes in the three altitude levels (80 m, 500 m and 2000 m) indicates that a magnetically active volcanic complex with a thickness of 100 m invokes at a height of 500 meters an anomaly with an amplitude of about 40 nT. In other words, a magnetic anomaly with a magnitude of 100 nT at an altitude of 500 m above the terrain represents a volcanic complex with a thickness of 200 m, a value of 200 nT, means a thickness of 500 m, and finally a value of 400 nT indicates a thickness of almost 1000 m. The thickness of the volcanic complex from the Slanské vrchy Hills, and Vihorlat Mts was interpreted similarly (Beneš 1971). In this case it was ascertained, that a volcanic complex with a thickness of 100 m recalls, at the altitude of 300 m an anomalous effect of 70 nT, a thickness of about 500 m causes an anomaly of about 350 nT and a thickness of almost 1000 m is depicted by an anomaly of about 700 nT. The interpretation of the thickness of volcanic complexes is given in the Atlas of geophysical maps and profiles (Kubeš et al. 2001).

Magnetic properties of minerals and rocks

The intensity of the magnetic properties of rocks depends directly on magnetic minerals, the (ferrimagnetic) content of magnetic minerals and on concentration within the rock volume as well. These are magnetite, ulvöspinel, maghemite, ilmenite and pyrrhotite. On the other hand, ulvöspinel, ilmenite and hematite are common examples of antiferrimagnetism and therefore the resultant magnetic susceptibility is not so impressive, due to internal magnetic structure.

Bulk magnetic susceptibility (κ — KAPPA) is the main parameter for rocks distinguishing from the magnetic point of view and according to this, magnetic rocks within Slovakia can be separated into the following groups:

- Practically non-magnetic — κ less than $300*10^{-6}$ units of SI;
- Very slightly magnetic — $\kappa = 300\text{–}1000*10^{-6}$ units of SI;
- Slightly magnetic — $\kappa = 1000\text{–}10{,}000*10^{-6}$ units of SI;
- Magnetic — $\kappa = 10{,}000\text{–}50{,}000*10^{-6}$ units of SI;
- Strongly magnetic — κ above $50{,}000*10^{-6}$ units of SI.

A voluminous magnetic properties study has been carried out on samples collected from natural and artificial outcrops and selected boreholes, as well. The magnitudes of magnetic susceptibility and remanent magnetic polarization (RMP) were assessed. Magnetic properties are given in the Table 1, according to data given by Husák & Stránska (1980), Grecula & Kucharič et al. (1985, 1992) and Gregorová et al. (2003). Variability in the parameters under study is obvious (this is the typical feature of magnetic rocks) and therefore the significance of average values is only on the informative level.

The variability in the presented results of the magnetic properties is mainly influenced by the following factors:

a) concentration and type of magnetic minerals;
b) magnetic properties of individual minerals;
c) type of magnetic mineral distribution in the rocks;
d) type and intensity of metamorphoses and tectonic activity;
e) weathering processes.

As we have mentioned earlier, the values presented in Table 1 are very roughly informative. Especially class of metamorphosed rocks is greatly variegated depending on the type of metamorphic processes.

On the basis of the data obtained, we can state that the group with practically no magnetic rocks includes the Quaternary sediments, Neogene sediments without volcanic fraction, sediments of the Flysch Belt and Paleogene units and almost the whole filling of the Mesozoic. The group of slightly magnetic rocks comprises fine-grained volcaniclastics, several types of slates, and metamorphites from the lower part of green schist facies, acid Permian volcanics and most of the granites. The group of moderate magnetic rocks is represented by medium-grained Neogene volcaniclastics, intermediate Permian volcanics, amphibolites and some types of mica schists, gneisses and granitoids. Coarse-grained volcaniclastics, breccias, and unfaulted products of andesite volcanism, paleobasalts, ultramafic bodies from the Meliaticum and Ochtiná tectonic unit and Rochovce granite are assigned to the group of strongly magnetic rocks.

Table 1: Magnetic properties of rocks.

ROCKS	Number of samples	KAPPA . 10^{-6} [SI]			RMP [nT]		
		min	max	X average	min	max	X average
Pre-Neogene							
Quartz porphyrs, porphyroids	19	61.54	831.60	253.71	1.22	188.56	60.90
Granites	664	0	708.38	24.24	0	612.00	0.76
Granodiorites and tonalites	710	0	27444.60	369.64	0	1094.68	10.82
Quartz diorites	13	0	16723.64	5085.32	0	368.72	95.05
Albitic-chloritic slates	40	0	365.75	44.96	0	1207.28	48.51
Chloritic-sericitic slates	19	0	0	0	0	0	0
Biotitic phyllites	19	0	487.70	25.67	0	1.22	0.06
Chloritic-sericitic phyllites	40	0	0	0	0	0	0
Mica-schists, Kohút zone, South Veporicum unit	35	0	7193.36	1115.71	0	164.84	43.62
Mica-schists, North Veporicum and Tatricum units	244	0	859.10	77.22	0	8.88	0.66
Paragneisses	124	0	36999.50	1343.81	0	307.47	13.05
Orthogneisses	156	0	19651.00	832.89	0	117.55	6.68
Migmatites	116	0	698.59	95.94	0	32.73	1.32
Amphibolites and other mafic rocks	253	0	104800.01	3481.98	0	1649.16	78.15
Serpentinites	162	0	74746.44	11832.94	0	8826.32	613.78
Quartzites (Paleozoic)	58	0	727.22	132.26	0	14.70	1.90
Dark phyllites (Paleozoic)	14	0	17343.48	5238.67	0	11434.46	4563.38
Arkose (Paleozoic)	20	0	0	0	0	0	0
Quartzites (Mesozoic)	57	0	616.07	49.20	0	19.00	1.77
Variegated shales (Mesozoic)	15	0	792.54	209.25	0	2.64	0.72
Sandy shales (Mezozoic)	10	0	0	0	0	0	0
Basalts (Hronicum)	75	0	83145.94	11957.23	0	7428.36	430.41
Neogenous+Quaternary volcanics							
Rhyolites	271	18.84	19230.62	2996.82	6.28	9663.66	1127.76
Rhyolite pyroclastics	144	310.23	13175.44	3999.10	14.44	2346.21	299.56
Rhyodacites	25	1760.91	15398.56	7067.51	18.84	1283.63	241.15
Dacites	10	7283.54	16973.58	12743.38	296.67	3594.80	1372.93
Pyroxenic andezites	1595	89.18	74480.80	23789.90	18.84	61898.19	2460.13
Amfibol-pyrox. andezites	25	7443.06	28437.10	16844.22	1458.84	2559.60	2200.76
Amfibol-biotit. andezites	215	639.30	47787.03	16748.76	10.05	5319.91	1307.87
Propylitized andezites	230	0	628.00	100.48	0	251.20	11.30
Pyrox. andesites pyroklastics	1802	339.12	44834.18	10304.22	18.59	24586.20	865.76
Bazaltic andesites	22	1369.04	26398.61	13367.61	405.94	5966.88	2385.27
Alkalic bazaltes, bazanites	76	2135.20	94137.20	30990.54	18.97	19123.86	5393.64
Basalts pyroclastics	31	18.84	8626.21	4270.40	2.14	1501.05	565.58
Quartz diorite (propylitized.)	435	0	43960.00	12220.88	0	728.48	242.41

In spite of remarkable variability in their magnetic properties, the basic knowledge of volcanic rocks about direct dependency between basicity and magnetic properties is valid. Moreover magnetic parameters can be extremely diminished in the central parts of Neogene volcanic zones where the secondary alteration (propylitization, adularization, silicification) was recognized. In this regard originally magnetic rock may be inverted completely into a non-magnetic medium.

Granitoids belong to special group, because for a long period they were considered as a non-magnetic medium within the territory of Slovakia. Verification of the Rochovce magnetic anomaly, by a deep borehole, ascertained the occurrence of magnetic granite of the Cretaceous age.

Since then we have learned that magnetic anomalies can also be created by tonalites, as well as by the special types of granites with mafic enclaves. Our contribution does not discuss the event of secondary magnetite creation in the processes of mechanical deformation and repetitive alterations, which are responsible for increase of magnetic properties (Grant et al. 1985). Clarification of these factors requires additional investigation. Some works have appeared regarding magnetic anisotropy study connected with tectonic-metamorphic events in the Veporicum (Hrouda et al. 2002).

Similarly, the group of metamorphosed rocks — mica schists, para- and ortho-gneisess mainly provide an extremely large range of bulk magnetic susceptibility and therefore are almost impossible to rank into one uniform category.

A review of the main magnetic complexes and their tectonic classification

The values for the intensity of magnetic field in Slovakia occupy a very wide interval extending from −1000 to +1100 nT, and thus produce variable types of magnetic anomalies depending on volume, shape, depth and magnetic properties of disturbing bodies.

Even a first view of the magnetic map (Fig. 1) shows, that a completely different magnetic field was recognized above areas, where Neogene and Quaternary volcanics occur.

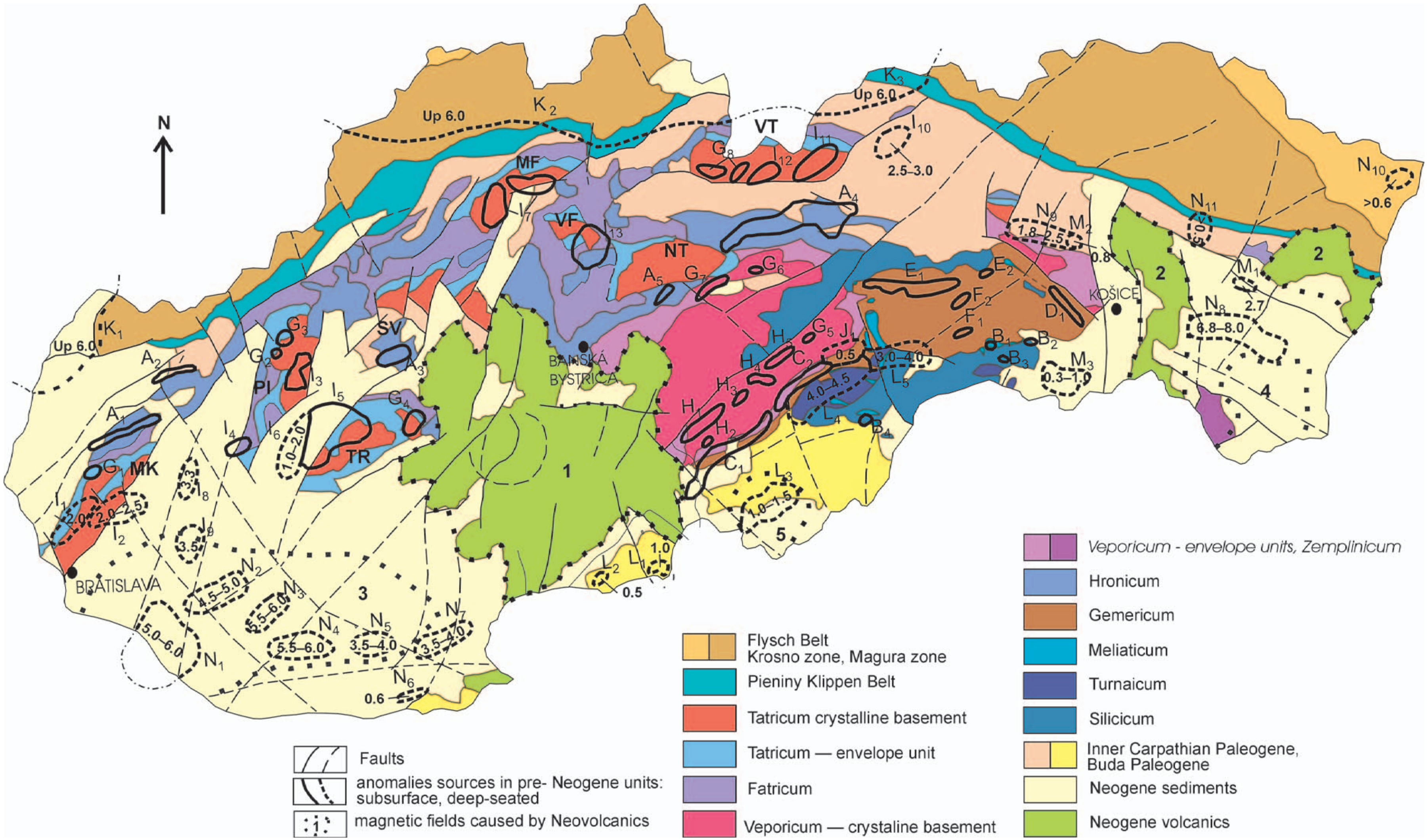

Fig. 2. Tectonic division of Slovakia (after Biely et al. 1996) and contours of magnetic anomalies. Anomalous magnetic fields caused by Neovolanics: **1** — the Central Slovakian volcanic field; **2** — the Eastern Slovakian volcanic field; **3** — buried volcanics in the Podunajská nížina lowland; **4** — buried volcanics in the Východoslovenská nížina lowland; **5** — the Southern Slovakian volcanic field. Contours of magnetic anomalies in pre-Neogene units: solid line — surface and subsurface anomalies; dash line — deep-seated sources, numbers indicate depth of upper edge of anomaly source from the surface. Core mountains: **MK** — Malé Karpaty, **PI** — Považský Inovec, **TR** — Tríbeč, **SV** — Strážovské vrchy, **MF** — Malá Fatra, **VF** — Veľká Fatra, **VT** — Vysoké Tatry, **NT** — Nízke Tatry.

These areas are depicted on the Fig. 2. Magnetic field is very variegated from both the morphological and polarity changes points of views. In spite of the very impressive features, the sources of the field are typically superficial — in the Central Slovak volcanic area. Deeper-seated volcanites, which create extensive anomalies in the Podunajská nížina Lowland (Gnojek & Kubeš 1991) and the Východoslovenská nížina Lowland (Gnojek et al. 1991), possess a smoother character of measured field and lower values as well.

The Western Carpathians are fundamentally structured in the sense of the Tectonic map of Slovakia (Bezák et al. 2004a) into Outer and Inner parts. The Outer Carpathians are composed of the accretion prism of Flysch Belt nappes, which are overthrusted onto the European Platform. The NW and N marginal part of Slovak territory contains anomalies caused by the effect of deep-seated Proterozoic rock complexes of the European Platform (Brunia), beneath the Flysch Belt.

The Inner Western Carpathians are created by three main Paleo-Alpine crustal units (Tatricum, Veporicum and Gemericum) and the superficial nappe systems of the Fatricum, Hronicum, Meliaticum, Turnaicum and Silicicum (Fig. 2). The crustal units contain fragments of Hercynian tectonic units. These tectonic units contain basic magmatic complexes, which are the sources of magnetic anomalies. There are basic volcanites in Mesozoic complexes of the Meliaticum and Upper Paleozoic complexes in the Hronicum and Ochtiná Unit (Vozárová & Vozár 1988). The Early Paleozoic primarily Hercynian tectonic units in the Gemericum also contain basic–ultrabasic volcanics (Rakovec, Klátov and Gelnica tectonic units). All these complexes are depicted on regional geological maps 1:50,000 (Bajaník et al. 1984).

The crystalline basement in the Tatricum and Veporicum comprises complexes of amphibolites and basic types of granitoids which are the source of magnetic anomalies. A peculiarity is an occurrence of mica schist complexes in the Southern Veporicum which possess high values of magnetic susceptibility. A special type is the Rochovce granite of Cretaceous age located in the contact zone between the Veporicum and Gemericum.

Other type of magnetic anomaly sources are deep seated, mainly in the basement of Neogene basins. Physical properties and tectonic coherence enable highly probable interpretations in some cases. Some of these rocks are verified by boreholes.

Over 60 magnetic anomalies in the territory of Slovakia (Fig. 2), induced by variable scales of petrographic types and age classifications have been recognized and described. It is necessary to stress that not all magnetic bodies are reflected on the presented map, due to its delimited proportion in relation to the network of measurements.

Compendium of magnetic anomaly sources

Anomalies on the magnetic map of Slovakia can be divided into the following basic groups:

- Magnetic anomaly sources in the pre-Neogene units;
- Magnetic anomaly sources induced by Neogene and Quaternary volcanic products.

Magnetic anomalies in the pre-Neogene units

Due to tectonic competence and lithology magnetic anomaly sources in the pre-Neogene units can be allocated as follows (Fig. 2):

Magnetic anomaly sources inside superficial nappes of the Inner Western Carpathians

A — mafic volcanics of the Hronicum
B — mafic and ultramafic volcanics of Meliaticum

Magnetic anomaly sources inside the Paleozoic basement of the Gemericum

C — mafic, ultramafic volcanics and phyllites of the Ochtiná tectonic unit
D — amphibolites and gneisses of the Klátov tectonic unit
E — mafic metavolcanics of the Rakovec tectonic unit
F — metavolcanics of the Gelnica tectonic unit

Magnetic anomaly sources in crystalline complexes of the Tatricum and Veporicum

G — amphibolites and metamorphic rocks with intercalation of mafic rocks
H — mica schists of lower Hercynian tectonic unit
I — basic varieties of Hercynian granitoids

Special type of deep-seated anomaly sources

J — Rochovce granite
K — Cadomian basement in the Northern zone of the Western Carpathians (Brunia)
L — combination of effects of Cadomian (?) basement in the Southern zone and its overlying units
M — ultramafic rocks
N — problematic magnetic anomaly sources.

In terms of morphology of anomalous field and probability of interpretation we can distribute anomaly sources into two groups:

a) located on the surface or at a shallow depth or deep-seated but verified by boreholes (group A–K and M);

b) deep-seated, newly interpreted or reinterpreted and problematic (group L and N).

Surface and subsurface anomaly sources

Permian basic and intermediate volcanic products from the Ipoltica Group (Vozárová & Vozár 1988) in the Hronicum (group A) caused the largest magnetic anomalies in the Malé Karpaty Mts (A_1, A_2) in the southern part of Strážovské vrchy (A_3) and in the Nízke Tatry Mts (A_4, A_5). All these volcanics are depicted in the regional maps with a scale of 1:50,000 (Maheľ & Cambel 1972; Maheľ 1982; Biely et al. 1993; Ivanička et al. 2007).

The Slovak karst territory in the South of Slovakia is characterized by the presence of a large number of bordered anomalies (B_1–B_4) with different amplitude (50–300 nT) which are assigned to the Meliaticum (Mello et al. 1996). The dominant sources of these anomalies are serpentinites whose development is fragmented due to tectonic activity and whose extension is small as well as the amplitudes of the anomaly field. Apart from the serpentinites, metabasalts, green shales and glaucophanites are developed here as well.

Anomalies in the Gemericum are found in the partial Ochtiná (C_1–C_2), Klátov (D_1), Rakovec (E_1–E_2), and Gelnica (F_1–F_2) tectonic units. Phyllites and shales, often with a high content of carbon component, represent the dominant rocks of the Ochtiná tectonic unit (Vozárová & Vozár 1988). Part of this unit is composed of mafic and ultramafic metavolcanics. The position of the unit in question is located in the northern part of the Gemericum, where it forms a narrow belt on the surface, but its subsurface parts can be interpreted very well thanks to magnetic results from the footwall of the Neogene unit.

A typical feature of the Klátov tectonic unit is the predominance of amphibolites, which are associated with gneisses, serpentinized spinel peridotites (antigorite serpentinite) and a negligible amount of crystalline carbonate as well (Spišiak et al. 1985). The Rakovec tectonic unit is a typical volcano-sedimentary formation with basic volcanites which are the main source of anomalies. The magnetic anomalies in the Gelnica tectonic unit are of local provenience and in most cases are generated by basic volcanics from a bimodal (diabase–keratophyre) formation, occurrences of which have been recognized both on the surface and at a shallow depth (Bajaník et al. 1984).

An anomalous effect of the amphibolite body in the crystalline of the Tatricum and Veporicum possessing a remarkable extension was recognized in the area to the NW of the Malé Karpaty Mts (G_1). According to the magnetic field configuration and modelling it is obvious, that the amphibolite bodies are not so thick (less than 300 m). On the other hand, the anomaly may be clarified as tonalite occurrences seated near the surface. Similarly, anomalies detected in the Považský Inovec Mts (G_2, G_3) are also caused by amphibolites. Less remarkable anomalies belong to amphibolite bodies with interpreted thicknesses of less than 300 m within the eastern part of the Tribeč Mts (G_4). Amphibolites contribute to the anomalies in the Slovenské rudohorie Mts together with the Muráň orthogneisses (G_5). The aggregate thickness of this complex is around 750 m. Amphibolites are responsible for anomalies within the Nízke Tatry Mts (G_6, G_7) and Západné Tatry Mts (G_8). Amphibolite bodies are depicted on the regional geological maps 1:50,000 (Maheľ & Cambel 1972; Klinec 1976; Biely et al. 1993; Nemčok et al. 1993; Ivanička et al. 1998, 2007).

A long zone of magnetic anomalies (H_1–H_5) caused by mica schists in a lower Hercynian tectonic unit in the sense of Bezák et al. (1997a) has been observed in the Southern Veporicum with the NE–SW orientation and with a length of almost 50 km. An elongation of this zone in the pre-Tertiary basement to the SW is interpreted by Gnojek (1989) as the Hurbanovo line.

Mica schists were displaced to the surface in the time of the paleo-Alpine transpression processes. They are depicted on the geological map of this region (Bezák et al. 1999). That is a reason why its shape is complicated, and this is equally reflected in the shape of the magnetic field. The magnetic properties of the mica schists are so massive, that their effect can be recognized even though the mica schists are covered by the 3 km thick granitoid complex of the middle tectonic unit. In contrast, the mica schists which are interpreted as a member of the middle lithotectonic unit in the sense of Bezák et al. (1997a) are mostly non-magnetic.

The average measured value of the magnetic field above the basic varieties of the granitoid environment (group I) is from 40–100 nT. It is clear, that the highest values are detected above the granite outcrops, or at shallow depths of less than 500 m. The granite bodies from the northern part of Považský Inovec Mts (I_3) and the central part of Tribeč Mts (I_5) can also be assigned to this group. In the majority of cases, magnetic bodies showed relatively smaller spatial extension as well as a smaller thickness. Amplitude value changes are not so remarkable with regard to the depth of sources and their thickness. It could imply deeper source localization, higher magnetic parameters and so also higher basicity. This assumption can be documented by geological-geophysical interpretation of the results of magnetic anomalies from the south-eastern part of the Malé Karpaty Mts (I_1, I_2), the southern part of Považský Inovec Mts (I_4), Rišňovská depresia Depression (I_6) and from the Central part of Podunajská nížina Lowland (I_8, I_9). In the area of the Malá Fatra Mts two anomalous areas (I_7) are delineated. The anomalies are sometimes accompanied by diminutive placement of amphibolites close to the surface. The magnetic effect of granitoids has been observed in the Vysoké Tatry Mts (I_{11}, I_{12}) and below the Paleogene sediments toward the East (I_{10}) and the Veľká Fatra Mts (I_{13}).

A very expressive magnetic anomaly has been detected near Rochovce village. It originates from the Rochovce granite (J_1) with high magnetite concentration. A structural borehole KV-3 found granitoids with extraordinarily high magnetic properties in the interval 600–1600 m (Hraško et al. 2002).

The anomalous field of the European Platform in the footwall of the Western Carpathians

This field has a deep source character which can be interpreted as the Brunia Complex (North European Platform) in the sense of Dudek (1980), underlying the flysch nappes. The Brunia Complex consists of magnetic and heavy rocks (gabroamphibolites, basic granitoids). These rocks have regional extensions to the SW into Austria (Gnojek & Heinz 1993) and to the NE into Poland (Żelazniewicz et al. 2009.)

The areas that belong to the NW part of Slovak territory contain two significant magnetic anomalies (K_1 and K_2). The central part of the above mentioned anomalies are located outside Slovak territory. The sources of both anomalies are intermediate, mafic, exceptionally ultramafic intrusive complexes in the Cadomian basement. These complexes subside gradually towards the South almost to depths of about 10–12 km and more (Pospíšil & Kadlečík 1991). Similar feature are assigned to the anomaly field K_3 in the N of Slovakia.

Influence of the supposed Cadomian basement in Southern Slovakia

On the basis of new data about the neo-Alpine tectonic development of the Western Carpathians (e.g. Ratschbacher et al. 1991; Csontos et al. 1992; Horvath 1993; Plašienka et al. 1997; Bezák et al. 2004a) the south part of the Western Carpathians consists of variable tectonic blocks-terranes which gradually closed the space of the Flysch basin. Tectonic units of the Southern Veporicum and Gemericum were placed in the north part of this area, which contains members with very high magnetic properties (mica schists, Ochtiná Group).

According to the 2D modelling results of anomalies (depth, extension and shape) it is clearly impossible to clarify the character of the magnetic field in this region by the effects of these bodies only (L_{1-3}). That was a reason, along with the occurrences of heavy mass in this region (Grand et al. 2002), why an additional source of magnetic field had to be added — the rocks with similar magnetic parameters as the Brunia block possesses. Such interpretation is supported by occurrences of xenoliths of unknown crystalline rocks, which were brought by magma in the Fiľakovo area (Konečný 2008). This complex underlying the mica schist complexes is probably an older basement on which have been deposited epicontinental mica schist packs.

Other regional anomalies (L_{4-5}) are situated in the surroundings of Rožňava town. The anomalies cover an area of almost 300 km^2. The upper edge of the magnetic complexes is interpreted as occurring at a depth 4–4.5 km below the surface. The extent of the anomalies and their magnetic and gravity properties make it very probable, that the magnetic echo originates from a combination of Ochtiná Unit rocks, mica schists of the lower Hercynian unit and fragments of the Cadomian(?) basement.

Ultramafic rocks

Other types of anomaly in the southern zones include ultramafic rocks, which represent remnants of the Meliata ocean subducted during the Jurassic period. These fragments are tectonically transposed mainly on the contact between the Western Carpathians and the Pelso Unit. The Komarovce body is a representative example of these anomalies (Gnojek & Vozár 1994).

The Komárovce magnetic anomaly (M_3) is one of the biggest in Slovakia. It is situated SW of Košice city. The anomaly reflects one of the largest ultramafic body in the Western Carpathians with an area of about 100 km^2 (Gnojek et al. 1991). The borehole KO-1 drilled in the 1960s discovered an ultramafic body at the depth of 943 m. The borehole was finished at the depth of 1543 m and remained in the ultramafic rocks.

The Zbudza anomaly (M_1) was detected in the northern part of the East Slovak Basin. The borehole Zbudza-1 drilled in the anomaly area caught a serpentinite body but only several meters thick — probably a marginal part of a magnetic body. The next anomaly was recognized to the south of Prešov town (M_2, Bzenov). The first interpretation of this anomaly was made by Gnojek et al. (1991). As a source of the anomaly, a body of ultramafic rocks is considered. The thickness of the body is approximately 600 m and its roof is thought to lie at a depth of 800 m. The declination of the magnetic body is towards the north.

Deep sources of anomalies in the pre-Tertiary basement in the South and East of Slovakia

The group of problematic sources of magnetic anomalies (N_1–N_{11}) in the bedrocks of the Tertiary sediments is the most difficult to interpret, because they are located mainly at very big depths and real knowledge about their origin is lacking. In most cases there are anomalies from the Danube Basin and the East Slovak Basin.

The most significant anomaly in the Podunajská nížina Lowland is the Gabčíkovo anomaly (N_1), which crosses the frontier into Hungarian territory. After the first measurements the anomaly has been reinterpreted by Gnojek & Kubeš (1991). Several deep boreholes in the anomalous area were drilled to the depth of almost 3000 m, long before this reinterpretation, but none has reached magnetic rocks in the Neogene filling, or bedrock. We suppose on the basis of the tectonic situation that the anomaly sources come from the crystalline complex of Tatricum, and/or Cadomian basement. Obviously, the origin of these rocks will be in mafic complexes, because heavy masses are detected in this area (Bielik et al. 1986).

Apart from these, the following two anomalies were detected in this area — Kráľov Brod (N_2) a Vlčany (N_3), which may be caused by basic differentiation of granitoids (Gnojek & Kubeš 1991).

In the wider surroundings of Kolárovo town an extensive but not very strong magnetic anomaly (N_4) has been detected. It is almost identical with a gravity anomaly (Sitárová et al. 1994). According to the interpretation given by Bezák et al. (1997b) the anomaly is caused by crystalline complex rocks, or mafic remnants of a Meliaticum inside the suture zone, which was utilized for the partial body's asthenolite rising during the extension process in the Neogene. The interpretation of the Strekov anomaly (N5) is clear because it shows the same features as the Kolárovo one (Filo in Kubeš et al. 2001).

From the depth localization point of view, the only exception is the Búč anomaly (N_6). Due to its shallow position, it is probably induced by mafic and ultramafic rocks in the Mesozoic bedrock. This anomaly probably does not belong to the Western Carpathians but to a block of the Pelso Unit. The source of the anomaly is only about 600 m below the surface.

The Bíňa anomaly (N_7) in the Eastern part of the Podunajská nížina Lowland probably derives from rocks of a mica schist complex (Gnojek 1989). The depth of the roof of this body is about 3–5 km. The anomaly is not located within magnetic sediments. The interpreted length is 17 km, width approximately 7 km. It is almost impossible to exclude the influence of Cadomian basement.

The Východoslovenská nížina Lowland is characterized by the dominant Sečovce anomaly N_8 (Gnojek et al. 1991; Gnojek & Vozár 1994). According to our present knowledge the bedrock complex (Inačovce-Kričevo Unit sensu Slavik 1974) comprises a set of phyllites of variable composition. However, this complex cannot be the source of the anomaly. The boreholes did not catch the bedrock complex. Therefore the source of the anomaly is probably metamorphosed mafic rocks at a depth of 6–8 km. It is probable that the Sečovce anomaly is connected with exhumation of subducted crust of the North Penninic ocean (Soták et al. 1993) and with intrusion of the Tertiary asthenolite (Bielik et al. 1998).

The Šariš anomaly (N_9) has been detected in the southern part of the Šarišská vrchovina Upland. The upper edge of it is thought to lie at a depth of 1.8–2.5 km. The reason for the magnetic field's configuration may be occurrence of more basic types of granitoid, but it is impossible to entirely exclude mafic rocks showing a connection with the North European Platform.

Anomalies N_{10} (Nová Sedlica) and N_{11} (Humenné) according to our preliminary interpretation (deduced from contemporary knowledge), are caused by a Neogene volcanics at a depth of more than 600 m. This is a completely new and astonishing finding.

Magnetic anomaly sources caused by Neogene and Quaternary volcanism products

The strongest magnetic anomalies in the territory of the Slovak Republic have been detected in the areas where the Neovolcanite Mountains are developed. These are characterized by quick alternation of positive and negative anomalies within a broad range — from –1100 to +1000 nT.

The manifestation of Tertiary volcanic rocks within magnetic maps depends on several factors including: magnetic properties, normal, or reverse magnetic polarization, intensity and type of hydrothermal alterations, planar and vertical extension of the magnetic body, volcanic complex composition, conditions of morphology, and methodology of use of geomagnetic mapping.

From the above mentioned factors, which influence the morphology and character of the magnetic field, perhaps the most dominant magnetic parameters are bulk magnetic susceptibility and normal, or reverse magnetic polarization. The rock complexes with reverse magnetic polarization are depicted in the magnetic maps by negative magnetic anomalies.

The value of magnetic anomalies directly depends on their planar and vertical magnitude. Volcanic rock bodies with small areal extensions and small thickness (less than 30 meters) need not be depicted by a real anomaly although geological mapping proved its presence. However, in several cases, anomalies were detected that are interpreted as magnetic bodies with larger dimensions which are covered by non-magnetic materials of various thicknesses.

Maps of magnetic anomalies from the Central Slovak and East Slovak Neogene volcanic mountains compiled by Gnojek (1989), Filo et al. (2003) furnished a picture of the three-dimensional distributions of magnetic active volcanic complexes.

Conclusion

The map presented in the contribution shows the first total picture of the West Carpathian rock complexes forming the whole territory of the Slovak Republic in the Earth's magnetic field. Almost all the measured anomalies have been described, most of them modelled and assigned to tectonic units as well.

The most disturbed magnetic field (from the configuration, intensity values and polarity changing points of view) has been ascertained above areas, where development of Neogene and Quaternary volcanics took place. The remanent magnetic polarization dominates over induced magnetic polarization in these formations.

Since we were often forced to use only estimated input data, where knowledge of magnetic properties is lacking, the possible mistakes may result in questionable depth of the magnetic body.

However, the morphological factor of the magnetic curve is the most decisive characteristic of the interpretation process and therefore this parameter appears the most significant for the study of tectonic style. The shape of magnetic bodies is linked to the magnetic curve and we believe this link is a crucial contribution to further uncovering and assessing the geological pattern and development with respect to particular localities.

The interpreted sources of magnetic anomalies have been classified according to both the tectonic competence and the lithology. The variability of the West Carpathian tectonic pattern as well as the sizeable depth of seating of volume magnetic sources is a reason why their interpretation is not definite and offers room for multi variant solutions. Apart from this, several cases have been observed in which an anomaly is generated by a superposition of various sources from different tectonic units.

The whole volume of recognized anomalies has been split into two groups: a) known, expressed by simple morphology, located on the surface, at shallow depths or verified by boreholes, b) reinterpreted or newly interpreted, mostly deep-seated and expressed by complicated morphology of anomalous field and problematic, where interpretation is insufficient according to our present knowledge.

Due to the fact that this is the first comprehensive description of magnetic anomalies in the whole territory of Slovakia it is obvious that the origin of some anomalies remains unknown or ambiguous. Therefore these magnetic rocks are suitable for further investigation.

It is beyond question that the map itself will serve as a suitable tool for structural and tectonic interpretations in the future from the regional point of view.

Additional magnetic measurements from regions, where they were missing, means an important step forward in the magnetic field characterization within the Central European space. The complete magnetic picture of the Slovak Republic will be one of the basic stones in the compilation of a magnetic map of Europe. For instance it makes possible investigation of important geotectonic zones such as the Cadomian belt on the boundary between the Bohemian Massif and the Western Carpathians and its continuation beneath the Alps and to the NE into Poland.

It is also important to investigate oceanic complexes from the point of view of reconstruction of the Alpine orogene. The big challenge for the future is an integrated interpretation together with seismic and gravity data.

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