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APPLIED GEOPHYSICS IN THE GEOLOGICAL PRACTICE OF SGIDŠ

Content

COVER: Detail of the radiometric map of Slovakia, distribution of eTh [ppm], map sheet 36, Banská Bystrica (Gluch, Dzurenda, Pramuka, 2011)

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Preface

In the structure of the State Geological Institute of Dionýz Štúr, the Department of Geophysics is among the relatively young workplaces. It was founded only in 1997 as response to the need to solve a wide range of outputs of geological-geophysical works in the scope of the Institute's geological tasks.

Undoubtedly, advantages of this solution include the fact that geologists and geophysicists could cooperate much more easily and more complexly than they did in previous decades when geophysical works were fully implemented in subcontracting.

The geophysicists have been involved in solving the results of research and exploration works and activities in the field of regional geology, hydrogeology, environmental geology, hydrocarbons inventory, geothermal energy, as well as in the field of information systems and technologies.

During the existence of the Department of Geophysics, several advanced and progressive methods and methodologies, as well as interpretative and visualization techniques have been designed and put into practice. Many of them are not currently used in similarly focused workplaces within the SR.

In retrospect, it can be said that for more than two decades this department has successfully established itself and has played a significant role in solving specialized tasks in which the solution of geophysical outcomes was a necessary prerequisite.

Augustín Gluch & Igor Zeman

LIST OF ACRONYMS

CSAMT	Controlled Source Audio-Frequency Magneto-Tellurics
DEM	Digital Elevation Model
EC	European Commission
ERT	Electrical Resistivity Tomography
Fm.	Formation
GfIS	Geophysical Information System
GPS	Global Positioning System
ICP	Inner Carpathian Palaeogene
ICRP	International Commission on Radiological Protection
IGRF	International Geomagnetic Reference Field
IP	Induced Polarization
LC	Lucas Cell
Mb.	Member
NRMP	Normal Remanent Magnetic Polarization
P-T	Pressure and Temperature
PMS GF	Partial Monitoring System of Geological Factors
RA	Reference Area
ROI	Region-of-Interest
RS	Reference Sample
RVA	Radon Volumetric Activity
SGIDŠ	Slovak Geological Institute of Dionýz Štúr
SGÚ	Slovak Geological Office (Slovenský geologický úrad)
S-JTSK	Unified Single Trigonometric Cadastral Network (Systém Jednotnej Trigonometrickej Siete Katastrálnej)
SP	Spontaneous Polarization
SR	Slovak Republic
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
VES	Vertical Electrical Sounding
WHO	World Health Organization

1. Geoelectrical Methods in the Past and To-Date in Slovakia

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Abstract: Geoelectric methods of Earth survey are an integral part of applied geophysics. For geologists, in addition to information obtained by gravimetry, magnetometry and seismics, important data on the electrical parameters of the geological environment, especially the resistivity, are provided. These indicators reflect the lithological properties of rocks. They help geologists in basic geological research and exploration, in refining the image of the geological environment in solving engineering geological and hydrogeological problems, solving environmental issues, etc. This contribution contains mainly information about the most used geoelectric method – vertical geoelectric sounding, its use in the geophysical survey of Slovakia, the processing and creation of a database of information. Whilst the practical application of the VES method has been in the agenda of powerful geophysical companies and organizations, the challenge of their systematic summarization has been taken up by employees of the SGIDŠ and the Geocomplex a.s. The result is relatively complex 2D information on resistivity characteristics of individual regions of Slovakia. Preferably, this is true of the Podunajská nížina Lowland area, where is covered by the highest density of VES measurements. At present, the VES method is often replaced by modern geoelectric methods, which are also discussed hereinafter, namely the CSAMT and the ERT methods.

Keywords: geoelectric methods, VES, resistance, databank, CSAMT, ERT

1.1 Introduction

Geoelectric methods, unlike gravimetry and magnetometry, which, due to their effective reach, deal with depth-sensitive issues up to several kilometres, are focused closer to the surface. The geoelectrics in Slovakia currently solve problems in the Earth's crust to depths in the order of several hundred meters. In the past, in the regions of lowlands and depressions, it was also 2 km. It complements its "bigger sisters within the geophysical disciplines" when uncovering the surface of the Earth's crust. What is missing in the scope of the survey, is replaced by the details of the information. Nevertheless, recently there is a clear shift in the use of this method from regional investigations to local surveys. The more modern world, the more electromagnetic ballast is present in the natural environment and thus the false information. It is also worth mentioning the constraints resulting from the topography along with the time as well as the economic factor. Therefore, modern geoelectric methods (e.g. ERT method) are used which, when combining classical geoelectric sounding and profiling methods, achieve remarkable results mainly in solving engineering geological and hydrogeological issues and environmental problems. It is also worth mentioning in Slovakia the non-traditional magnetotelluric methods, which quite successfully replace the classic VES technique.

1.2. Division of geoelectric methods and brief theory of the most used VES method

Geoelectric methods represent a relatively wide range of geophysical methods, which can be characterized and classified according to various criteria. Certainly, the most commonly used method in the Slovak Republic is the vertical electrical sounding method, which uses a unidirectional current and examines the relative resistivity of the environment in the vertical direction. Its complement is a method of resistivity profiling in various geometric variants (symmetrical, combined, dipole, etc.), which examines the change of the average resistivity of the environment in the horizontal direction. Both of them are therefore called the **resistivity** ones. Table 1.1 gives a brief overview of the relative resistivity of basic rock types.

Tab. 1.1 Specific resistivities of rocks

Rock type	**Specific resistivity ρ_z** (ohmm)
loam	$1 – 10^2$
clay	$10 – 10^2$
sand	$10^2 – 10^4$
saturated sand	$1 – 10^1$
sandstone	$10^2 – 10^4$
limestone	$10^2 – 10^4$
conglomerate	$10 – 10^4$
granite, syenite	$10^2 – 10^5$
diabase, basalt, gabbro	$10^2 – 10^5$
schists	$10^2 – 10^4$
claystone	$10 – 10^3$
quartzite	$10^3 – 10^5$
marble	$10^2 – 10^5$
gneiss	$10^2 – 10^4$

In Slovakia, in addition to these two methods other geoelectric methods have been also used, which can be termed as **potential**. In the ore survey, but also in solving the engineering geological and hydrogeological issues, the

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method of the charged body and the submerged electrode method were applied. They use unidirectional current, but unlike the VES, they are exploring the distribution of the electric field potential.

Similarly, two geoelectric methods using the effects of **electrochemical processes** are used in ore exploration and environmental problems. It is a passive method of spontaneous polarization (**SP**) or the active method of induced (activated) polarization (**IP**) method. The first one examines the natural electric field generated in the oxidation-reducing environment, for instance of, sulphide deposits; the second one examines a temporary electric field induced by an electrical pulse. Both of these methods were often used in field geophysical surveys in the ore deposits areas of Slovakia.

In addition to these methods, which only examine the parameters of the electric field, geoelectric methods also include the so-called **electromagnetic methods**. These include, in the past the widely used very low frequency (VLF) method utilizing the signals of very long wave transmitters. It was used to locate the tectonics. It is also worth mentioning the ***turam*** and ***slingram*** methods used in ore exploration and localization of tectonic lines and zones. Electromagnetic methods also include the magnetotelluric sounding method, which examines the natural magnetotelluric field of the Earth, or artificial arrays of specific wavelengths according to the need of exploration. Nowadays, the Controlled Source Audio-frequency Magnetotellurics (**CSAMT**) method is gradually being promoted in Slovakia, which uses artificial active sources to detect a specific resistivity of the environment. These artificial sources produce magnetotelluric fields with a frequency of 1 – 8000 Hz and their reach is at a maximum of about 2 km. The CSAMT method has the ambition to replace the classic resistivity sounding – the VES method.

Given that the largest and most important volume of information on the resistivity conditions of the Slovak geological environment is contained in the data obtained from VES measurements, it is appropriate to briefly mention the basics of the VES method.

Measurement of VES consists in the creation of an artificial electric field using the so-called current electrodes, referred to as A and B (Figure 1.1). These electrodes extend along the line from the measuring point, each to the opposite side, depending on the depth range. At the point of measurement there is a receiver that measures the voltage of the field by measuring electrodes known as M and N. From the values of the current I [mA] and the voltage ΔV [mV] between M and N and the constants for the given geometry of the arrangement, we calculate the apparent resistivity of the environment $\boldsymbol{\rho_z}$, which is a function of the depth of measurement, i.e. extension length AB.

$\rho_z = k \, . \, \Delta V/I$

where **$k = \pi \, . \, (AM \, . \, AN)/MN$**

AM, AN, MN are the distances among electrodes

In the past, the calculated values of $\boldsymbol{\rho_z}$ have been exported to bilogarithmic cross-sections and quantitatively interpreted using a set of theoretical curves – so-called pal-

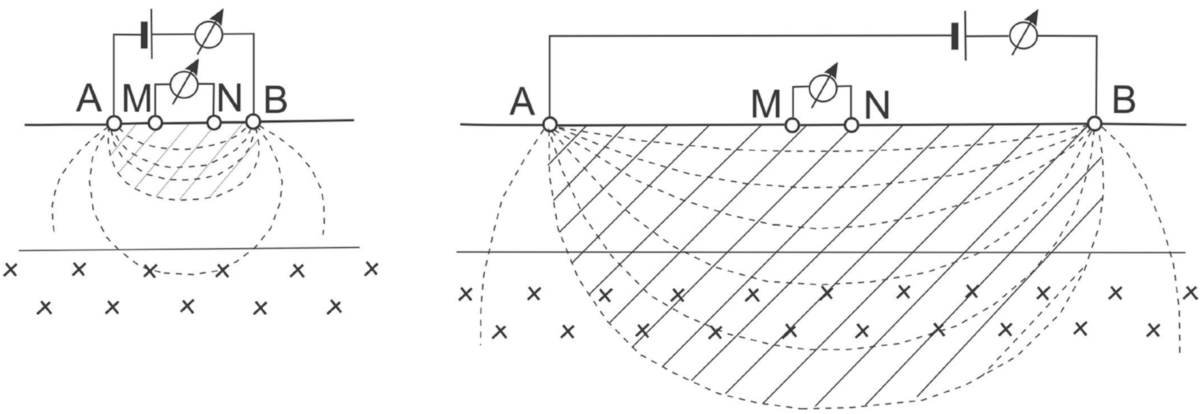

Fig. 1.1 *Electrode displacement diagram for VES measurement, dependency of depth reach upon spacing of current electrodes A – B*

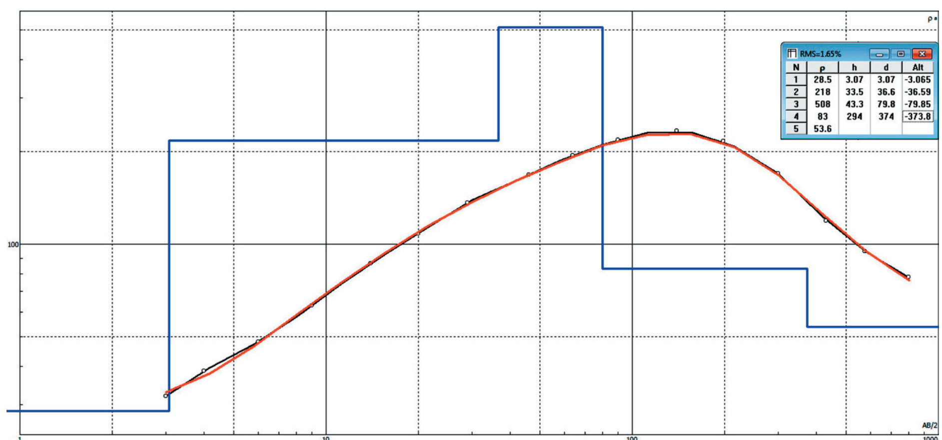

Fig. 1.2 *Quantitative interpretation of VES curves using IPI-2Win*

lets. Currently, several programmes replace quantitative palette interpretation, for instance IPI2Win (Figure 1.2).

The results of the interpretation are geophysical, or geophysical-geological 2D sections. By processing a larger number of VES measurements within certain area, the possibilities of construction of ρ_z maps are created (Fig. 1.3). With a sufficient density of interpreted VES supplemented by information from wells, a 3D image of the environment can be constructed (Figure 1.4).

1.3 Level of investigation of the territory of Slovakia by VES measurements

The basis for the assessment of level of investigation of the territory of the SR by geoelectric measurements (VES) provides the review presented in the framework of the task "Evaluation of Hydrocarbons in Selected Areas of the Western Carpathians" (Janků et al., 1996) as well as its evaluation in "Atlas of Geophysical Maps and Profiles"

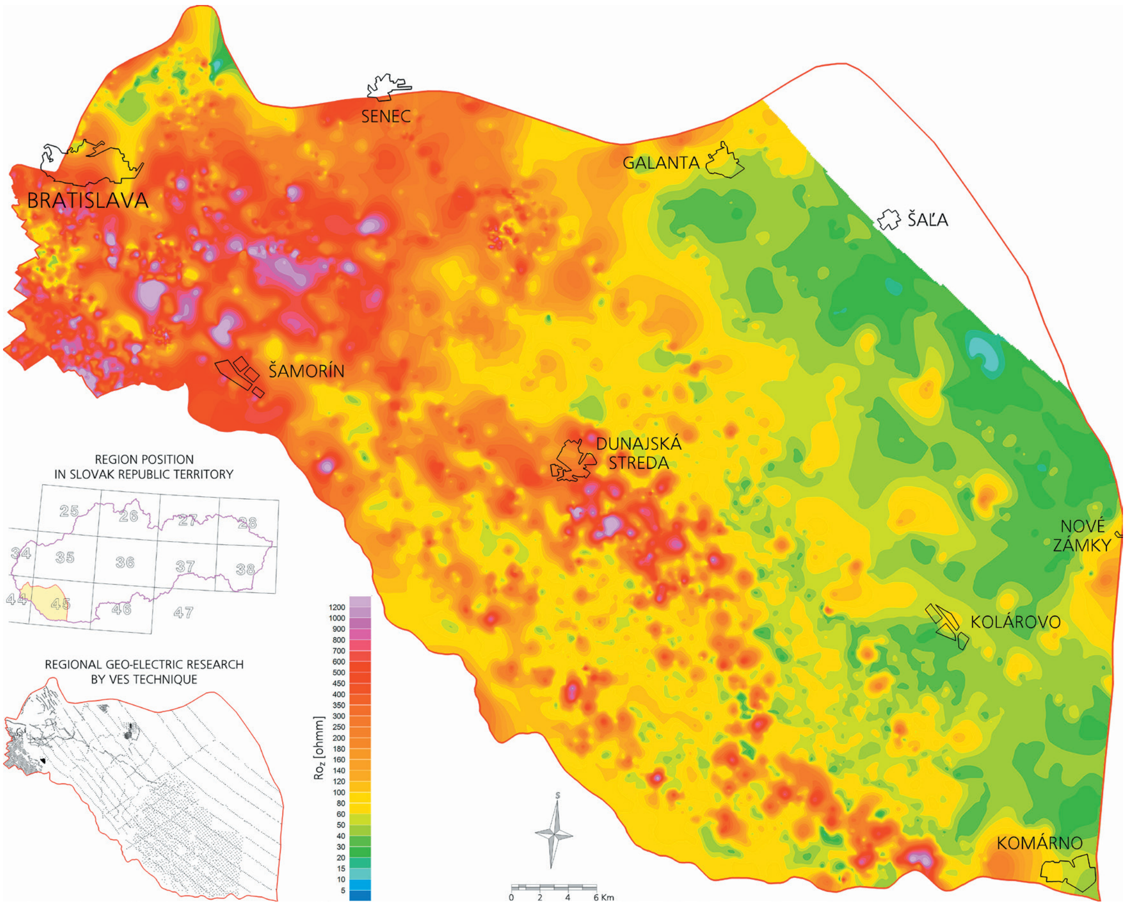

Fig. 1.3 *Podunajská rovina Flat; Map of apparent resistivity for AB/2 = 10 m*

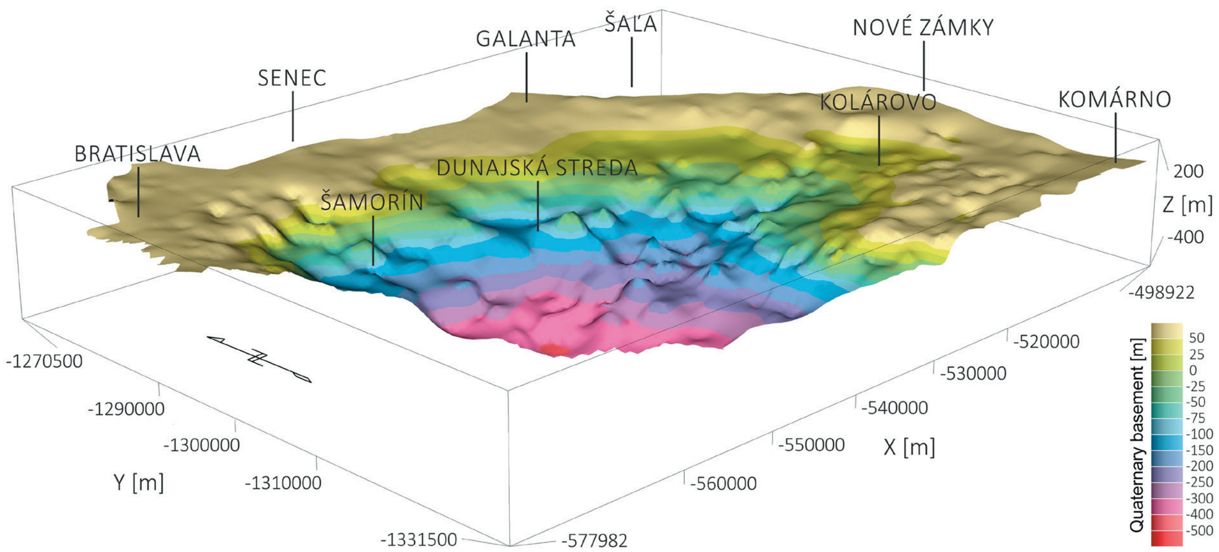

Fig. 1.4 *Podunajská rovina Flat; 3D map of the relief of the Quaternary basement (Z = 20 x elevated)*

Kubeš et al., 2001, hereinafter Atlas). The VES measurements with AB intervals of two or more kilometres were performed for various purposes. The measurements were made mainly from the area of the depressions and the contact between the basins and the mountain ranges, or in the areas of exploration for mineral and thermal waters. The VES measurements with AB 4 km were mostly located only in the centres of the basins to map a relief of the fundament.

Another group was focused in the geological setting and ore prospecting, especially in the volcanites of the Western Carpathians. They were used mainly for the search of feeder systems and tectonics (Vtáčnik, Banská Štiavnica-Hodruša ore district, Javorie, Poľana, Slanské vrchy, Pezinské Karpaty Mts.)

A separate group was focused on survey of areas with coal horizons in order to solve the geological structure. The largest regional scope included VES with AB spacing 16 km to search for geological structures with oil and gas occurrences (Záhorská, Podunajská and Východoslovenská nížina Lowlands). These measurements belong among the oldest within the SR territory.

The measurements of regional significance include VES on the 2T and GI regional profiles (Figure 1. 5), realized for the purpose of solving the deeper geological setting as well as measurements in the Spišsko-gemerské rudohorie Mts.

When designing a map of geophysical indices and interpretations (MGII), the VES measurement in regions were reinterpreted. In other areas outside the MGII regions, they have not yet been re-evaluated to the level of new geological knowledge.

As can be seen from the previous brief survey, over the past 70 years of the existence of geophysics, there were carried out around ten thousand VES profiles across the whole of Slovakia. Given that the information value of these primary data is still up-to-date, attention will be paid to the processing of these measurements and their preservation for further use in geological practice.

The widest network of VES measurements is in the Podunajská nížina Lowland region, and therefore the quality of information from the VES interpreted in this region is high. The last geophysical work of a regional character, which completed the field measurements in this region, was the Podunajsko-DANREG report (Kováčik, M., Tkáčová H. et al., 1996).

Apart from the Podunajská nížina Lowland, the authors also interpreted the southern part of the Záhorská nížina Lowland and the southern part of the Malé Karpaty Mts. The workload consisted of the Danubian Lowland, where, after completing measurements in locations with insufficient VES density, the resistivity maps for AB = 200 and 600 m were constructed. The main result of the interpretation of geoelectric measurements is the map of the thickness of the Quaternary at a scale of 1 : 100,000 and maps of the thickness of the Pannonian to the Pliocene at a scale of 1 : 200,000.

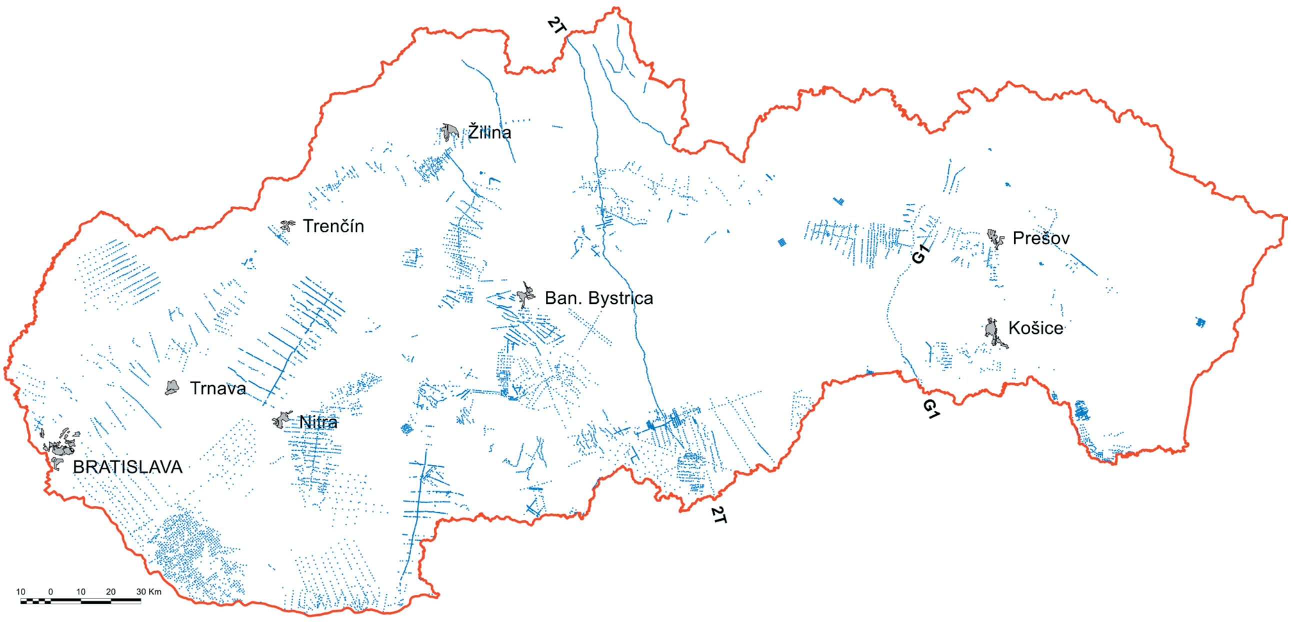

Fig. 1.5 *Arrangement of VES measurements processed in Atlas (Kubeš et al., 2001)*

Separate profiles with VES measurements are located in the Malá Fatra Mts.and Orava region, three profiles in the area of the Lipany deep boreholes and others in the elevation "Bystré" (Košice Basin). An important group of VES geoelectric measurements are measurements made in the scope of the exploration survey for the radioactive waste repository. These measurements were located in the mountain ranges of Tribeč, Žiar, Veporské and Stolické vrchy, Cerová vrchovina Upland and Rimavská kotlina Basin.

One of the first geophysical tasks with a goal to compile a VES measurement database, namely VES with an AB = 2,000 and larger spacing, was "Atlas of Geophysical Maps and Profiles" (Kubeš et al., 2001). In addition to VES data, the "Atlas" contains also gravimetric, magnetometric and radiometric measurements from the territory of

Slovakia. The processing of geoelectric measurements of VES in this report consisted of an archival excerpt. Individual VESs (carried out from 1966 to 1999) were selected from archives of geophysical workplaces across Slovakia (Geocomplex a.s. Bratislava) and the Czech Republic (Geofyzika s.p. Brno). The next step was the digitization of VES from the final reports. The reading and insertion of the parameters of the interpreted depths and resistivities on map sheets of SR 1 : 50,000 basic map was the next step. Altogether 11,185 VES were processed, of which 1,140 original materials are archived in Brno. From the obtained geoelectric parameters, the maps of the measured resistivity from the three selected regions were compiled for 3 depth levels along with vertical resistivity profiles. Following the re-interpetation of VES measurements, geophysical-geological sections were constructed.

In the database, the VES designation is based on the original scrapbook, the coordinates in the S-JTSK geographic coordinate system, the AB electrode stretch azimuth, the numerical code of the final report and the implementing organization, the type and quality of the measurements, the depth and resistivity interpreted and its value measured in three to five AB/2 = 300, 600, 1,000, 1,300 and 1,600 m (Geocomplex a.s., Bratislava) or AB/2 = 200, 500, 1,100, 3,100 and 6,500 m (Geofyzika a.s., Brno). The authors of the database assumed that the most utilised parameters would be the AB/2 levels and the measured resistivity at the given level. From these parametres, it is possible to construct resistivity maps for individual depth levels.

A sufficiently dense network of measurements is projected for the construction of a robust resistivity map, flatly distributed over time. These conditions are mainly met by VES measurements in the lowlands and basins. Most measurements are located in Podunajská panva, Lučenská and Rimavská kotlina, Turčianska kotlina, Hornádska kotlina Basins and Žitavská pahorkatina Upland (Figure 1. 5). Three regions – Podunajská nížina Lowland, Lučenská and Rimavská kotlina and Turčianska kotlina Basins – were selected for the compiling the resistivity maps. In these regions, the density of the VES distribution is sufficient to be theoretically interpolated between the measured values. The resistivity maps are designed for AB/2 = 300, 600 and 1,000 m, representing the depth ranges 120 – 150 m, 250 – 300 m and 400 – 500 m.

Another important project focused in the database processing of geoelectric measurements was completed in 2008. The geophysical archive, register and databases of geophysical data were created, which includes a database of VES measurements (Gluch et al., 2003). The GEOMIND project has also been involved in this task in order to build an international metadata database, including the VES AB = 200 to 6,000 m probes processed to solve the project in question.

The last work on the creation of the VES database was the project "VES Databank – Turčianska kotlina Basin and part of the Podunajská pahorkatina Upland" (Gluch et al., 2013). The outline of this databank is presented in Figure 1. 6. Its content has a high informative value, which hides complex work with archival data of various nature. Two working groups were collaborating in parallel, one of which was made up of GEOCOMPLEX staff and the other employees of the SGIDŠ.

At the GEOGOMPLEX's workplace site-specific sketches were collected. The VES positions were redrawn into topographic maps of the same scale as those reported in the reports. From the Archive of Geofond and GEOCOMPLEX, individual reports were subsequently selected and, after the analysis, they were handed over to SGIDŠ workers to scan various graphic, text and table documents. The documents were scanned at 150 dpi (text attachments), or 300 dpi (graphical attachments and necessary computer processing (rotation, cropping, digital filtering, and grooming) were archived on optical media in TIFF or JPEG formats. All-in-all 27 individual reports were scanned and processed, representing a total of 1,661 graphical raster files from A4 to A0 format, with a volume of nearly 30 GB of data (before digital processing and raster compression).

A review of geoelectric sounding investigation level with designation of VES objects was carried out, along with drawing out the probe profiles from each reviewed report and showing the azimuth of the extension of the electrodes. The data were processed in the MicroStation CAD software. In the course of solving the geological task in question, all available archived relevant bases of

X	Y	Z	Mapa	OBJEKT	VES	Profil	Lokalita	Rok	Azimut	typ VES	rozostup	kvalita	arch. č.	Ro1	H1	Ro2	H2	Ro3	H3	Ro4	H4	Ro5	H5
-500845	-1266936	140.12	45-21	VES_VII-19	19	VII	Nitra	1966	45	1	200	1	01-17539	9.0	2.5	117.0	5.0	19.0					
-500765	-1266869	140.17	45-21	VES_VII-20	20	VII	Nitra	1966	45	1	200	1	01-17539	9.0	2.2	108.0	3.3	25.0					
-500698	-1266806	140.00	45-21	VES_VII-21	21	VII	Nitra	1966	45	1	200	1	01-17539	12.0	2.3	207.0	4.5	21.0					
-500628	-1266749	139.58	45-21	VES_VII-22	22	VII	Nitra	1966	45	1	200	1	01-17539	12.0	2.6	144.0	7.4	19.0					
-500539	-1266691	138.43	45-21	VES_VII-23	23	VII	Nitra	1966	45	1	200	1	01-17539	11.5	3.0	115.0	6.0	22.0					
-500463	-1266635	138.57	45-21	VES_VII-24	24	VII	Nitra	1966	45	1	200	1	01-17539	11.0	2.0	132.0	4.0	20.0					
-500383	-1266569	142.93	45-21	VES_VII-25	25	VII	Nitra	1966	140	1	200	1	01-17539	34.0	3.0	306.0	1.5	30.0					
-502183	-1267743	139.92	45-21	VES_VIII-03	3	VIII	Nitra	1966	140	1	200	1	01-17539	17.0	3.0	153.0	3.0	21.0					
-502137	-1267704	140.01	45-21	VES_VIII-04	4	VIII	Nitra	1966	130	1	200	1	01-17539	14.0	3.3	126.0	3.3	20.0					
-502075	-1267645	140.24	45-21	VES_VIII-05-03	5-03	VIII	Nitra	1966	130	3	200	1	01-17539										
-502075	-1267645	140.24	45-21	VES_VIII-05	5	VIII	Nitra	1966	130	1	600	1	01-17539	25.0	3.2	58.0	3.2	21.0	57.0	100.0			
-502001	-1267581	140.27	45-21	VES_VIII-06-04	6-04	VIII	Nitra	1966	45	4	200	1	01-17539										
-502001	-1267581	140.27	45-21	VES_VIII-06	6	VIII	Nitra	1966	45	1	200	1	01-17539	17.0	3.5	153.0	3.5	20.0	60.0	60.0			
-501926	-1267522	140.07	45-21	VES_VIII-07-04	7-04	VIII	Nitra	1966	45	4	600	1	01-17539										
-501926	-1267522	140.07	45-21	VES_VIII-07	7	VIII	Nitra	1966	45	1	200	1	01-17539	15.0	5.5	136.0	1.5	10.0	4.5	150.0	5.0	11.0	27.0
-501847	-1267460	140.00	45-21	VES_VIII-08	8	VIII	Nitra	1966	45	1	200	1	01-17539	11.0	1.3	44.0	1.7	14.0	3.8	45.0	7.0	10.0	
-501771	-1267402	140.00	45-21	VES_VIII-09	9	VIII	Nitra	1966	45	1	200	1	01-17539	17.0	4.0	170.0	4.0	20.0					
-501698	-1267330	140.00	45-21	VES_VIII-10	10	VIII	Nitra	1966	45	1	200	1	01-17539	11.0	2.2	99.0	4.4	21.0					
-501616	-1267264	140.00	45-21	VES_VIII-11	11	VIII	Nitra	1966	45	1	200	1	01-17539	14.0	4.6	112.0	9.2	23.0					
-501537	-1267196	140.00	45-21	VES_VIII-12	12	VIII	Nitra	1966	45	1	200	1	01-17539	11.5	3.5	105.0	7.0	12.0	7.5	104.0	6.0	20.0	
-501463	-1267132	140.00	45-21	VES_VIII-13	13	VIII	Nitra	1966	45	1	200	1	01-17539	15.0	3.7	135.0	3.7	16.0	2.0	73.0	7.0	22.0	

Fig. 1.6 *Databank VES – Turčianska kotlina Basin and part of Podunajská pahorkatina Upland (cut-out)*

measurements of VES with AB range from 200 to 4,000 m in defined interest areas were completed. All the primary materials were collected in one place and were gradually inserted into input forms (MS Excel format), in the structure and physical content designed to solve the geological task of a similar focus (Gluch, A., 2008). In parallel, data of all VES objects were digitalized from the original map – in the S-JTSK geographic system (Křovák's projection). The altitudinal elevations of the individual objects (Z [m a.s.l.]) were added to the unified VES measurement database from the digital terrain relief model (DMR, grid 50 x 50 m, in Kubeš, P. et al., 2001).

The VES database contains 1,348 VESs from the area of Turčianska kotlina Basin (area approx. 359 km^2) and 3,957 VESs in the part of the Podunajská pahorkatina Upland (area approx. 3,100 km^2), i.e. together 5,305 VES in both areas of interest, with all the necessary data and information to be applicable to their possible (re) interpretation. In addition to the VES measurement database, scale 1 : 50,000 topographic documents were produced, in which the outputs of the task solution were finalized and visualized in graphical (printed) form. In electronic form (in the OASIS montaj GIS environment), the results are presented for individual interest areas at scale 1: 50,000.

After taking into account the outputs of the previously realized geological task "Databank of Geophysical Measurements – Vertical Electrical Sounding" (Gluch, A., 2008), a complex area of 8,328 km^2 (Podunajská rovina Flat and part of Podunajská pahorkatina Upland) with 10,939 VES probes has been assessed. The Geophysical Information System provides comprehensive and reliable background information and data on VES measurement and results.

The importance and quality of data processing from VES measurements in such databank could be evaluated and evaluated in the reinterpretation of these data within the task "Map of Geophysical Indices and Interpretations, Podunajská rovina Flat Region" (Kucharič et al., 2015). In addition to maps of apparent resistivity for AB/2 = 10 m (Figure 1. 3), 50 m, 100 m and 300 m, providing information on the geoelectric quality (≈ lithology) of the environment at different depths, a map of the thickness of the Quaternary (Figure 1. 7) was compiled, which is the result of a quantitative reinterpretation of VES measurements from the territory in question. Similarly to the maps of apparent resistivity, this map was constructed at a scale of 1 : 100,000. For a given scale, the density of information was 1 VES/km^2. After selecting individual VESs, these were fully reinterpreted by a single methodology using IPI2win. The built-in database was graphically processed in applications of Oasis montaj and MicroStation environ into the map of Quaternary deposits thicknesses. The map itself gives an interesting picture of the thickness of gravels/sands, whose importance lies primarily in the accumulation of high-quality groundwater. It confirms the well-known fact that the thickness of these sediments is in the order of hundreds of meters with a maximum in the Horný Bar Village where, according to VES measurements, it exceeds 500 m.

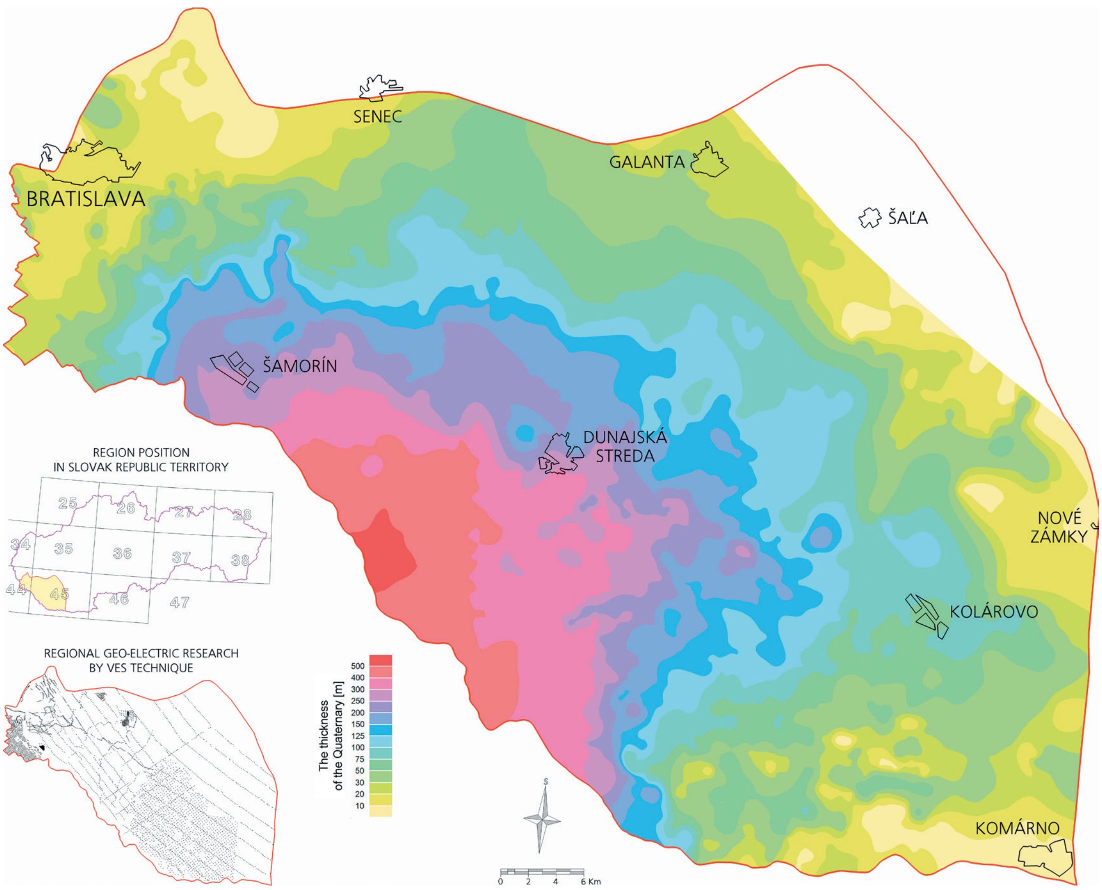

Fig. 1.7 Podunajská rovina Flat; Map of the Quaternary deposits thickness

1.4 Use of geoelectric methods at present – new trends

At present, geoelectric methods are used differently when compared to the past (about 25 years back). Given the fact, that the volume of finances in the environmental sector has been decreasing regularly, the focus of work with the use of costly VES geoelectric measurements with deep reach has shifted to less expensive geoelectric measurements. It is a survey of the shallow parts of the Earth's crust, the first tens of meters, of the engineering geological and hydrogeological conditions of the geological environment, the archaeological survey and the research aimed at the protection of the environment. The exception is a geoelectric survey aimed at studying the suitability of the environment for radioactive waste disposal, CO_2 storage and geothermal energy sources exploration search, addressing the geological problems in the depths of hundreds of meters or more. Here too, VES measurements with deep reach are used, but they are limited by the presence of artificial electromagnetic fields – dispersion currents. This is why the magnetotelluric sounding method – CSAMT (magnetotelluric sounding with a frequency of 1 – 8,000 Hz), which offers a "X-ray" view of the distribution of resistivity in the rock environment, is increasingly being promoted. Similarly to the VES method, but in shorter time, less costs, and without the impact of topography and interfering electromagnetic fields, it can divide the rock environment according to the interpreted resistivity. In Figure 1. 8 is a schematic sketch of the transmitter-receiver arrangement at measuring by this method.

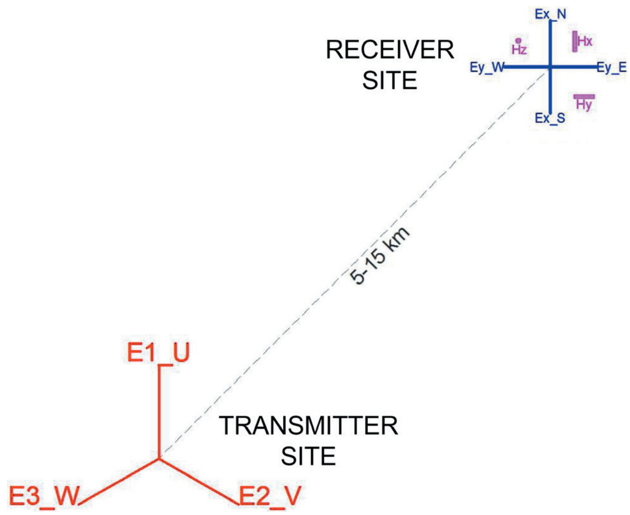

Fig. 1.8 *Scheme of CSAMT measurement*

The depth range of the CSAMT is within 1.5 km, under ideal conditions approximately 2 km. It depends on the frequency of the active transmitter, which can vary in the range of 1–8,192 Hz. The measurement time depends on the measurement conditions and ranges from 20 to 120 minutes. In addition to exploring the deeper levels of the geological environment, the CSAMT method also finds its firm place in geological survey, mapping of geological structures, impregnation zones, delimitation of the deposit body, and determination of homogeneity of rock formations. It can also be used in depth engineering geological surveys before tunnel construction and hydrogeological and geothermal exploration.

Another method, which has a relatively wide scope, is the Electrical Resistivity Tomography (ERT). It is a complex resistivity measurement system with a larger number of electrodes. The spacing of the electrodes is determined depending on the detail and the required depth range, the

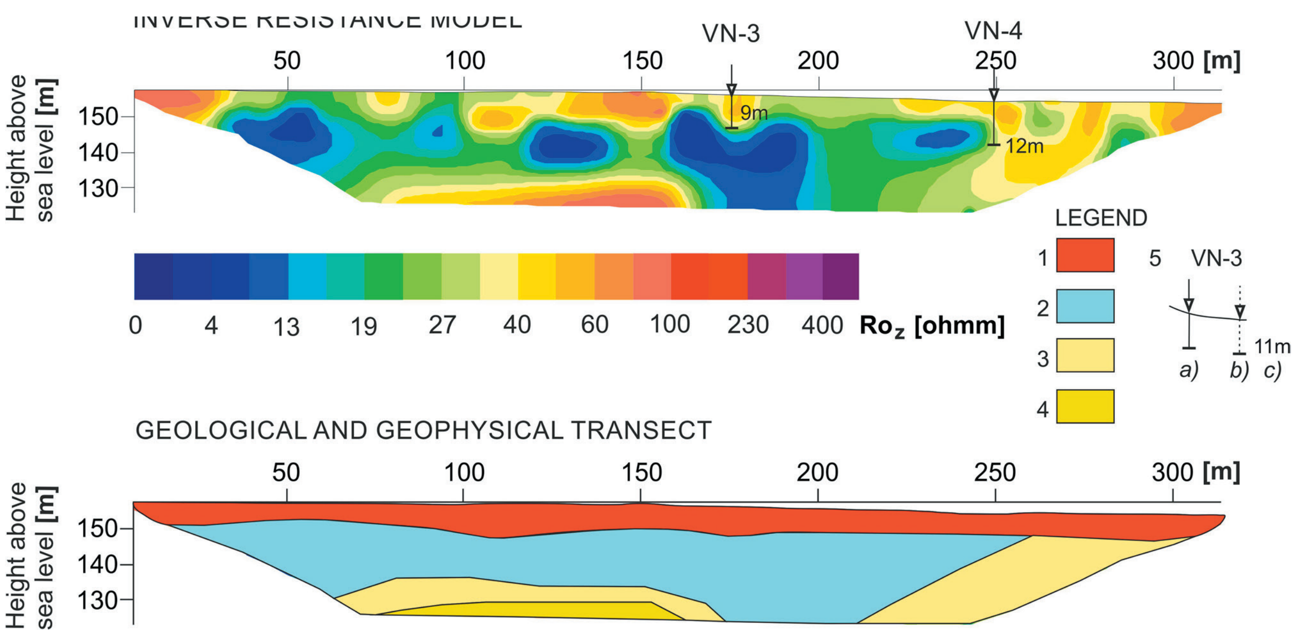

Fig. 1.9 *Geological survey of environmental burden at the Devínska Nová Ves site (Volkswagen landfill) – results and interpretation of ERT (measurements on profile P3, Slaninka, et al., 2015)*

Legend – 1: anthropogenic sediments; **2**: sediments with predominantly clay component; **3**: sediments with prevalence of sand component; **4**: undivided cemented sediments (clay, silt, sandstone, conglomerate); **5**: label of geological-exploration well, a: borehole on profile, b: borehole depth [m] electrodes serving alternately as source or measuring. Due to the fact that the measurements are carried out using a series of electrodes extended with a relatively dense step (max. about 5.5 m) and a computer-controlled addressing of the current and voltage reception, a relatively detailed picture of the apparent resistivity in vertical section along the measured profile can be retrieved. Subsequent computer processing allows the measured data to be transformed into a set of realistic resistivity values and, by using available geological documentation from exploratory wells, to obtain an image of the local site of the rock environment along the measured geophysical profiles (Figure 1. 9).

1.5 Conclusions

The geoelectric methods used in Slovakia currently reflect the current state of Slovak geophysics. In practice, financially less costly methods are used, since companies dealing with geoelectric measurements and geophysics are generally small, staffing and capital considerably less stable than they used to be in the past. The original system, built on a single state organization that dealt exclusively with geophysics and geophysical groups at powerful geological companies, had given geoelectric methods greater scope for use, especially in terms of workload and thus practical experience. At present, geoelectricity in Slovakia is significantly atomized. Groups of geophysicists are small, although they are able to respond to the diverse needs of the Slovak customers, but larger state orders and the needs of foreign clients where financially demanding geoelectric methods are to be used, are solved with large difficulties. Therefore, the geoelectricity in Slovakia has now shifted the focus of its exploration into the shallow parts of the geological environment or into the office for statistical processing.

At the SGIDŠ the work on geoelectrics is mainly based on the geoelectric data, which are contained in geophysical reports. These include, in particular, their database processing, the creation of a VES measurement database and a meaningful assignment to regional geological works in the form of maps of geophysical indices and interpretations (MGII). Small-scale field geoelectric work, which mostly addresses the problems of engineering geological and hydrogeological character, is also worth mentioning.

The future of geoelectrics and geophysics is, in general, hidden, as in other human activities, in the youth and in its interest in this discipline. Therefore, greater emphasis should be placed on the promotion of geological and environmental science disciplines. They also supply associated geological sciences, such as geoelectrics and geophysics in general, to address their roles and needs.

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2. General Maps of Natural and Artificial Radioactivity

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Abstract: The use of radiometric methods in geological practice is conditioned by the presence of about 70 radionuclides in a geological environment. An important contribution was, for example, the introduction of gamma spectrometry, but also some of the commonly used emanation methods into the complex of geophysical works.

After the advent of specialists on natural and artificial radioactivity at the Department of Geophysics at the SGIDŠ, the relevant results of gamma spectrometry began to be used not only for the creation and construction of complex geophysical information systems (Atlas of Geophysical Maps and Profiles, Geological Information System of the SGIDŠ), at the geological research and evaluation environmental factors, but also in addressing a number of other geological issues.

Taking into account the extent and diversity of the projects solved, the authors of the submitted paper focused only on some selected tasks, from the gradual development of the processing methodologies and the actual status of graphical output creation, to advanced sophisticated geological and geophysical information systems.

Keywords: gamma spectrometry, natural and artificial radioactivity, radon risk

Introduction

The possibility of using radiometric methods is due to the presence of a wide range of radioactive elements in rocks, waters and the atmosphere. Approximately 340 different nuclides were found in the natural environment, of which approximately 70 are radioactive.

One of the basic methods used for the decades to determine the parameters of natural radioactivity is gamma spectrometry (GS). Using various types of field gamma spectrometry apparatus, contents of natural radionuclides (potassium, uranium and thorium) can be determined “in situ”, which is a significant qualitative shift compared to total gamma radiation.

Radioactivity of rocks

The most prominent natural radionuclides involved in the total radioactivity of the rock environment include potassium ^{40}K, uranium ^{238}U and thorium ^{232}Th.

The ^{40}K potassium isotope (source of beta and gamma rays, half-life of 1.28 x 10^9 years) breaks down into a stable element and has a proportion of 0.012 % in the natural mixture of potassium isotopes. Potassium is very widespread in the lithosphere and, together with silicon, sodium and calcium, is the main rock-forming element. Under certain temperature and pressure conditions, potassium becomes mobile and accumulates mainly in K-metasomatosis processes.

Gamma-spectrometric determination of potassium concentrations is based on the detection of gamma rays of ^{40}K radionuclide emitting gamma quanta with an energy of 1.461 keV. Determination of potassium content is direct and expressed in % K.

The average *potassium* content in the Earth’s crust is about 2.6 %. On the territory of Slovakia its content ranges from 0.1–6.1 %, at an average of 1.3 %. The lowest values (below 1.0 % K) are recorded over carbonate sediments in different geological units. Among the rocks with increased average concentration, it is possible to include Permian and Triassic slates, sandstone, arcoses and greywackes (3.5–4.8 % K), some Veporicum granites (3.0–3.2 % K), Gemericum granites , 0–4,4 % K), metarhyolites and their tuffs in Spišsko-gemerské rudohorie Mts. and rhyolites of Central Slovakian neovolcanites (4.1–6.1 % K), (Gluch in Káčer et al., 2014).

Uranium in the natural mixture consists of isotopes: ^{238}U, whose share is up to 99.275 %, ^{235}U with 0.72 % and ^{234}U with only 0.005 % share.

Radionuclide ^{238}U, with a half-life of 4.47 x 10^9 years, breaks down into daughter products that are also radioactive. These further decay and form a long decay line ending with a stable ^{206}Pb lead isotope. This so-called uranium decay line has 19 radioactivity intersteps and contains the most significant and most studied natural radionuclides – ^{226}Ra radionuclide (alpha and gamma radiation source with a half-life of 1,600 years) and radon ^{222}Rn (source of alpha radiation with a half-life of 3.825 days). Since uranium is a highly mobile element, under natural conditions, the radioactive equilibrium between ^{238}U and ^{226}Ra occurs quite often due to physical or chemical changes in the rock environment.

The isotope ^{235}U has a half-life of 7.04 x 10^8 years and produces an actinium series, which terminates after the fifteenth intervals of radioactive transition with a stable lead isotope of ^{207}Pb.

Determination of uranium contents by GS is made possible by detecting gamma radiation with the energy of 1.764 keV radioisotope ^{214}Bi from the decay series ^{238}U. It is therefore indirect and is expressed in terms of equivalent uranium content (ppm eU).

The uranium is present in the rocks in three forms: it forms separate minerals, it is contained in rock-forming and accessory minerals, and it is also dispersed in the matrix. The levels of equivalent uranium in the Earth's crust are in the range of 2–4 ppm eU. In the Western Carpathian region, its concentrations are in the range of 0.1–17.4 ppm eU, at an average of 2.6 ppm eU. The lowest average concentrations (below 2.0 ppm eU) are over some calcareous claystones and sandstones of the Outer Flysch and over carbonates of different geological units. For rocks with an increased average content (above 4.0 ppm eU), it is possible to include tuffogenic sandstones and slates of the Younger Palaeozoic, some Gemericum granites, rhyolites of Central Slovak and Zemplín neovolcanites and some dolomites of the Middle to Late Triassics (so-called "uranium dolomites"; Gluch in Káčer et al., 2014).

Thorium ^{232}Th (the half-life of 1.41 x 10^{10} years) is the parent element of the thorium decay series, which terminates after ten members of radioactive transition with a stable ^{208}Pb isotope. Indirectly, in thorium equivalents (ppm eTh), the thorium contents are also expressed by measuring the activity of the radioactive isotope ^{208}Tl from the ^{232}Th decay series when detecting gamma rays with an energy of 2,615 keV.

It is a lithophilic element that concentrates in later stages in the magmatic differentiation and replaces elements of rare earths in minerals. The main form of thorium mobility is a mechanical transport. The thorium is characterized by geochemical stability. Thorium is a stable element found in three forms in the rocks – one of the main crystalline elements, in the crystalline lattices isomorphically representing other elements and dispersed in the matrix.

Average concentrations of thorium in the Earth's crust are in the range 8–12 ppm eTh. In the territory of Slovakia its contents reach 0.1–29.8 ppm eTh, at an average value of 7.7 ppm eTh. In the Western Carpathians the lowest concentrations are above the sandstones and claystones of the Outer Flysch. The rocks with the highest average concentrations include, in particular, the rhyolites of the Central Slovakian Neovolcanites and the Triassic variegated shales and sandstones (above 20 ppm eTh; Gluch in Káčer et al., 2014).

By natural radioactivity measurements it is possible to search for radioactive raw materials, to map and to radiologically characterize various lithological and structural geological elements, to monitor the course of fault lines and, under favourable conditions, to conduct research on non-radioactive raw materials. It is also possible, however, to deal with other assignments if the object under consideration is radically different from the environment. The limiting usability factor of GS is its relatively small depth range, practically not exceeding the first tens of centimetres.

Accounting for the extent of the geological issues solved in the Department of Geophysics within the last two decades, the authors of the paper devote more detail to only some of the key projects, the results of which, on regional scales, cover vast areas or the whole territory of the Slovak Republic.

GAMMA SPECTROMETRY – NATURAL RADIOACTIVITY

2.1 Atlas of Geophysical Maps and Profiles

The first of the major projects of the newly created Department of Geophysics was the "Atlas of Geophysical Maps and Profiles" (Kubeš et al., 2001). In its part "Natural Radioactivity" (Čížek, 2001), the aim was to create a harmonized dataset of gamma spectrometric information and to compile maps of natural radioactivity of the territory of SR at 1 : 500,000, 1 : 200,000 and 1 : 50,000. An autonomous part was the mapping of anomalous gamma spectrometric objects and their lithostratigraphical evaluation.

2.1.1 Methodology and results of realized works

The primary task of the project solution was to verify the available data and to calculate the results of ground measurements to a uniform radio-geochemical level. As a basis, GS data were taken from the work "Geochemical Atlas" (Daniel, 1997). The reason for this was the fact that the GS measurements, realized in the period of 1991 – 1994 in the whole territory of Slovakia with an average density of 1 reference sample (RS) per 10 km^2, were obtained by one type of calibrated terrain equipment, using the same methodology, the results of field measurements were linked to laboratory testing and evaluated by a team of experienced investigators.

All other backgrounds (including GS results) were converted (levelled) to a uniform radio-geochemical level using Geosoft's software application (Geosoft Inc., Toronto, Canada). At the same time, gross errors and inaccuracies in primary databases (erroneous position of measured objects, inaccurate measurement results not corresponding to the local geological structure, etc.) were removed. The result of the work was the first database of ground measurements GS (27,486 objects), which became the basic data base for building individual maps in the Geosoft (Oasis montaj) GIS application.

The results of airborne GS were only available in the form of monolayer grids of 125 x 125 m for the entire surface area (almost 1.8 million points for each component, Figure 2. 1).

Digital geological maps of the Slovak Republic were not available at that time and the generated maps correspond to the technological level of their origin time – they were visualized in the form of mono-element grids (grid-kriging method, grid size – 125 x 125 m). Nevertheless, at that time it was a significant shift in the complexity of the processing and the aggregate evaluation of the results of measurements of ground and airborne GS on the territory of the Slovak Republic (Figure 2. 2).

2.2 Geological factors of the environment

Since the early 1990s, the outputs of the measurements of the components of natural (but also artificially-induced) radioactivity have begun to be used to address the geological issues under the unifying title "A set of regional maps of geological environmental factors". Over the past

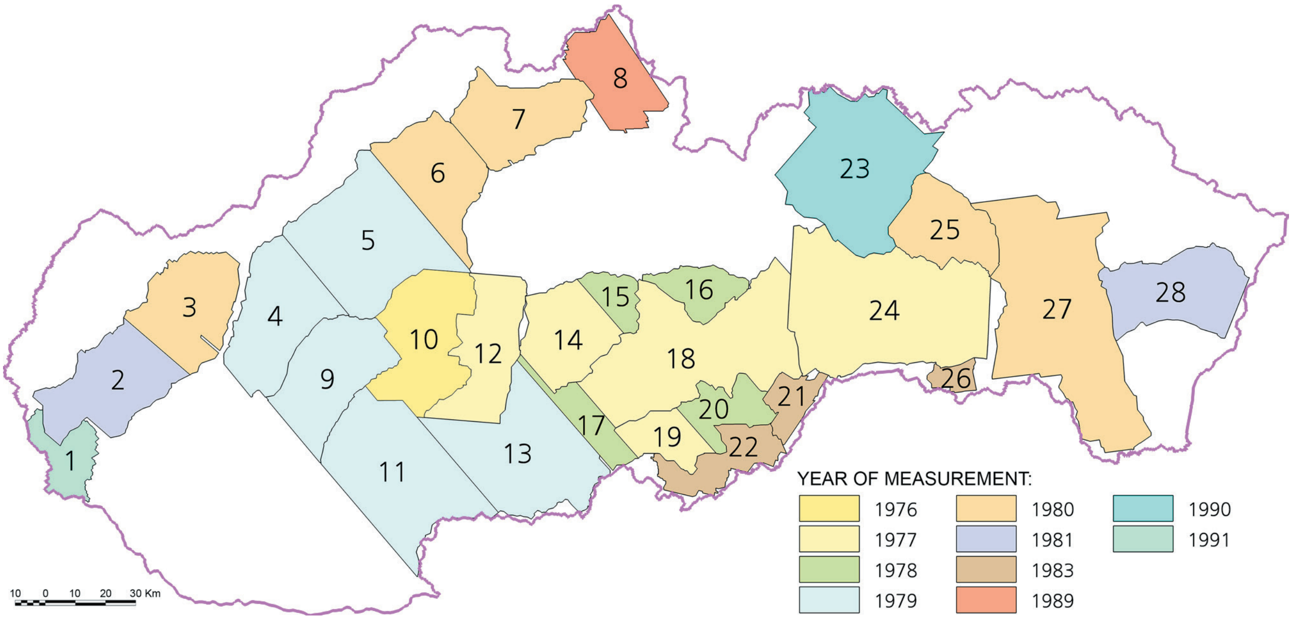


Fig. 2.1 Regional review of the Slovak territory by airborne gamma spectrometry
Regions – **1:** Great Bratislava; **2:** Malé Karpaty Mts. – SW; **3:** Malé Karpaty Mts.– NE; **4:** Považský Inovec Mts.; **5:** Strážovská hornatina Mts.; **6:** Martinské hole Mts.; **7:** Malá Fatra and Oravská Magura Mts.; **8:** Orava Region; **9:** Tribeč Mts.; **10:** Vtáčnik and Pohronský Inovec Mts.; **11:** Krupinská vrchovina Upland; **12:** Kremnické and Štiavnické vrchy Mts.; **13:** Krupinská vrchovina Upland; **14:** Poľana – Javorie Mts.; **15:** Ľubietová Zone; **16:** Muránska planina Plateau; **17:** Krupinská vrchovina Upland – E; **18:** Slovenské rudohorie Mts. – W; **19:** Lučenská kotlina Basin; **20:** Rimavská kotlina Basin – W; **21:** Rimavská kotlina Basin – E; **22:** Cerová vrchovina Upland; **23:** Levočské vrchy Mts.; **24:** Slovenské rudohorie Mts. – E; **25:** Branisko – Čierna hora Mts.; **26:** Košická kotlina Basin – S; **27:** Slanské and Zemplínske vrchy Mts.; **28:** Vihorlatské vrchy Mts.

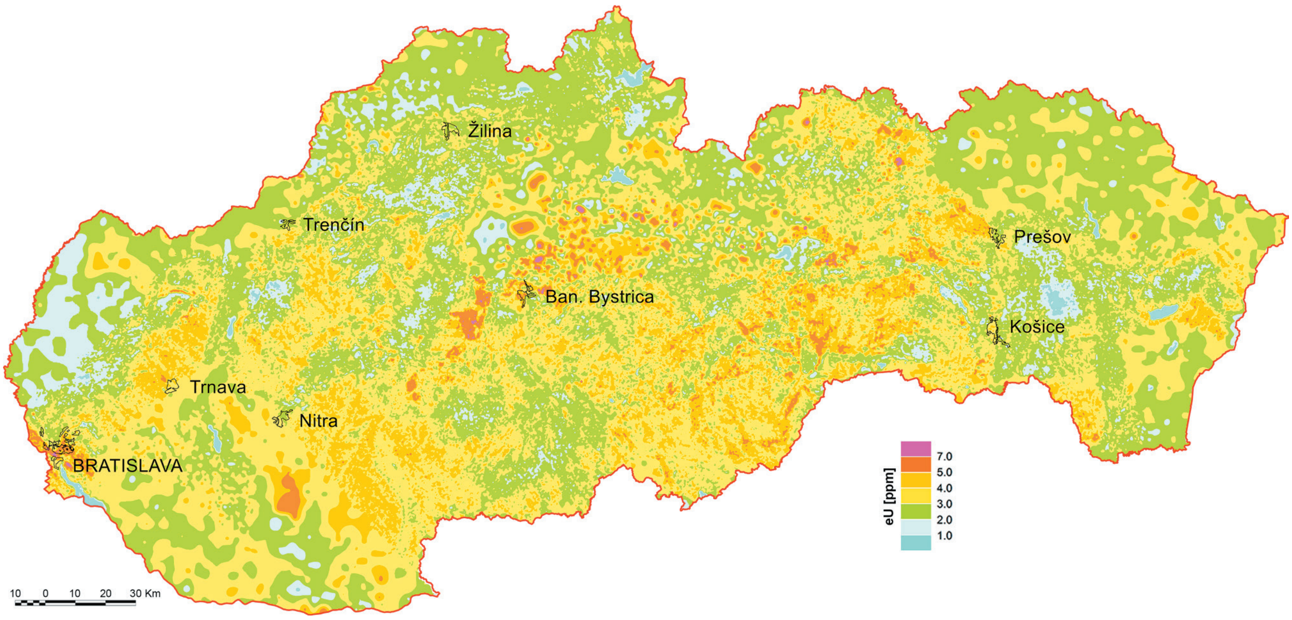


***Fig. 2.2** Concentrations of equivalent uranium eU [ppm] in the territory of the Slovak Republic*

decades, several geological exploration organizations and dozens of investigators have been involved in their solution. The output maps at scale of 1 : 50,000 (to a lesser extent 1 : 25,000) along with text explanations in the form of final reports already cover about 2/3 of the territory of Slovakia. The rest of the territory is mapped at a scale of 1 : 200,000 (Figure 2. 3).

The aim of the individual geological tasks was to compile maps of natural and artificial radioactivity in defined regions at a scale of 1 : 50,000 in the range – radon risk forecast, uranium equivalent (eU), total natural radioactivity (eUt) and natural radioactivity in water. In accordance with the amended Directive no. 1/2000-3 of the Ministry of Environment of the Slovak Republic they have been later supplemented by a gamma radiation dose map (Da) and a map of risk factors from natural and artificial radioactivity. The solution included general maps at 1 : 200,000 – the concentration of potassium (K) and thorium (eTh), including the map of the surface activity of the isotope of the caesium (^{137}Cs – if not directly measured in the sense of

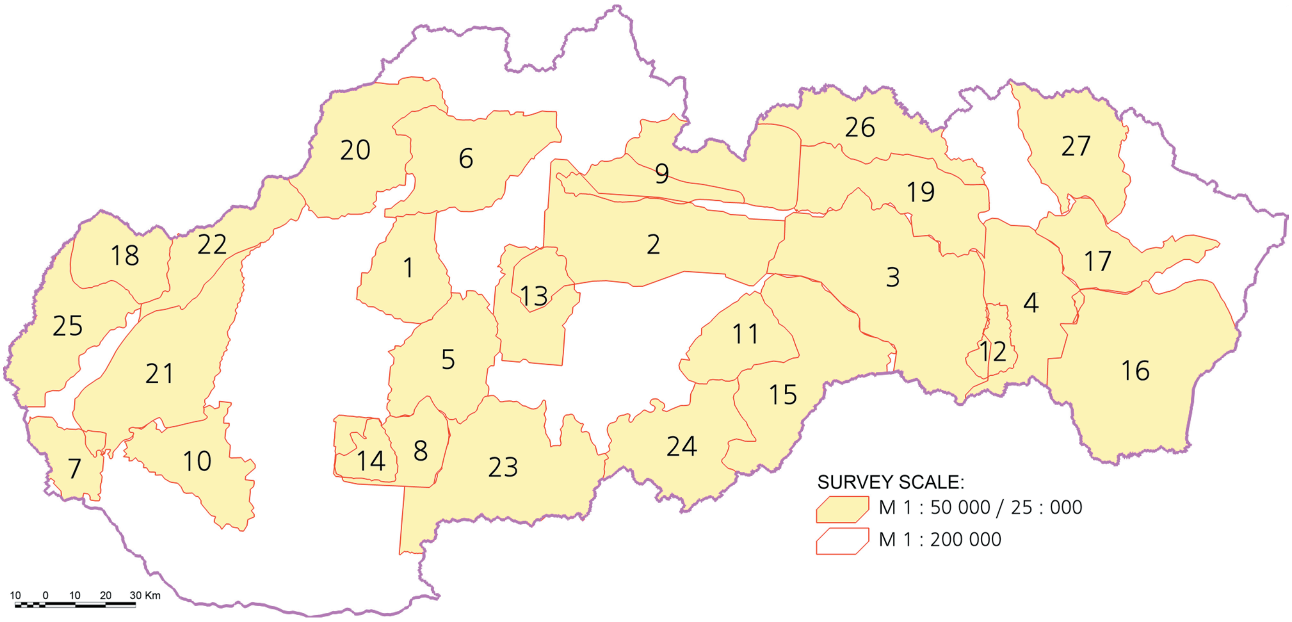


***Fig. 2.3** Regional survey of the Slovak territory by ground gamma spectrometry*

Regions – **1:** Horná Nitra; **2:** Nízke Tatry Mts., Starohorské vrchy Mts., Bystrická vrchovina Upland, Čierťaž; **3:** Hornádska kotlina Basin and E part of the Slovenské rudohorie Mts.; **4:** Košická kotlina Basin and Slanské vrchy Mts.; **5:** Žiarska kotlina Basin and Banská Štiavnica region; **6:** Malá Fatra Mts. And parts of adjacent basins; **7:** Great Bratislava; **8:** NE part of the Levice District; **9:** Vysoké Tatry Mts. and Liptovský Mikuláš – Ružomberok; **10:** Galanta; **11:** Jelšava – Lubeník – Hnúšťa; **12:** Košice – City; **13:** Banská Bystrica – Zvolen; **14:** Levice – Mochovce; **15:** Slaná catchment in the Rožňava District; **16:** TIBREG; **17:** Vranov nad Topľou – Humenné – Strážske; **18:** Chvojnická pahorkatina Upland; **19:** Poprad and Upper Torysa catchment; **20:** Middle Váh River catchment; **21:** Trnavská pahorkatina Upland; **22:** Myjavská pahorkatina Upland and Biele Karpaty Mts.; **23:** IPREG; **24:** Lučenská and Rimavská kotlina basins; **25:** Záhorská nížina Lowland; **26:** Ľubovnianska vrchovina Upland; **27:** Ondavská vrchovina Upland

project assignment, they were generated from the archives stored in geophysical databank of SGIDŠ).

2.2.1 Methodology and results of realized works

The baseline for compiling K, eU and eTh concentrations, eUt and Da values were the in situ GS measurements. The measurements were made by the portable gamma spectrometers of several manufacturers – mostly GS-256/GS-512 (Geofyzika a.s., Brno, Czech Republic) – which are among the top instruments in their class.

The field GS in the area of the evaluated regions was made in the network of measured points in order to achieve (including archival data) an average density of 1 point/km^2. The measured points (objects) were geologically documented and their position was plotted in the terrain in topographic maps at a scale of 1 : 50,000/1 : 25,000. The geographic positions of the objects were subsequently later modified by various processes in the S-JTSK coordinate system (the unified single trigonometric cadastral network – Křovák).

At a later time when GPS (Global Positioning System) receivers became available, the geographic coordinates of the objects were recorded in the digital recorder of the GPS device, and processed in the S-JTSK. The altitude of the measured objects was initially read from map data. After 2001, since the digital elevation model (DEM), which was developed for the "Atlas of Geophysical Map and Profiles" project (Kubeš et al., 2001), the altitude was generated from this model (grid 50 x 50 m).

The natural radioactivity parameters (K, eU and eTh) were measured directly at the surface (the vegetation cover was removed; the measurement geometry was 2 π; the measurement time-span 3-6 minutes). The total natural radioactivity, expressed in equivalent uranium concentrations of eUt, was additionally calculated according to the relationship:

$$\mathbf{eUt}\ [ur] = 2.79 \cdot \mathbf{K}\ [\%] + \mathbf{eU} \cdot [ppm] + 0.48 \cdot \mathbf{eTh}\ [ppm]$$

From the measured values, the dose rate of gamma radiation in atmosphere – Da – was also calculated, used for assessing the radioactivity of the rock environment:

$$\mathbf{Da}\ [nGy.h^{-1}] = 13.139 \cdot \mathbf{K}\ [\%] + 5{,}701 \cdot \mathbf{eU}\ [ppm] + 2.506 \cdot \mathbf{eTh}\ [ppm]$$

The validity of determination of concentrations of natural radionuclides was assessed by field measurements and by comparison with the results of laboratory determinations of collected samples of soils and rocks. The alignment outputs were processed in the form of linear regression dependencies, according to which the calculated concentrations of natural radionuclides were recalculated to the laboratory assay level. Subsequently, they were transformed into a uniform radio-geochemical level of the territory of the Slovak Republic, i.e. to the level of the data of the unified gamma spectrometric database (geophysical database of the SGIDŠ) in the studied area and they became thus ready for further processing.

Not all of the lithotypes within the evaluated region could be radiologically evaluated in a given survey scale (the density of the GS points measured) and thus the evaluation possibilities were relatively limited. This often resulted in the distortion of outputs (Figure 2. 4a), where we present a method of processing during that period by commonly used techniques. The measured data were visualized using a suitable software application (most commonly Surfer, GoldenSoftware, USA).

In interpreting the results of GS measurements and constructing maps of natural radioactivity, the digitized geological maps of the evaluated regions have been used for the last two decades as well as one of the interpretation layers. At that time, advanced interpretation techniques were developed at the SGIDŠ Department of Geophysics, in which the principle of geological analogy was widely used. The results of GS interpretation, including their visualization, have reached a qualitatively incomparably higher level than that previously achieved (Figure 2. 4b).

2.3 Geological Information System – GeoIS

The Geological Information System – GeoIS Project (Káčer et al., 2014) is one of the most important activities of the SGIDŠ in the area of information systems, which is currently continuing its second phase.

One of a number of geophysical measurements processed and included in the system were also regional measurements by gamma spectrometry. The aim of the task was to compile new general maps of natural and artificial radioactivity at 1 : 500,000 and 1 : 200,000 (concentrations: K, eU, eTh, values: eUt, Da, spatial activity ^{137}Cs, radon risk, natural radioactivity of water).

The resulting maps (Figure 2. 5) were constructed on the basis of the outputs of the task "General Geological Map of the Slovak Republic at 1 : 200,000" (Bezák et al., 2008). Other supplementary sources of information (structural geological, hydrogeological, engineering geological and archive radiometric data and data from the SGIDŠ database) were also taken into account.

However, the main objective of the solution was the compilation of updated sets of maps of geofactors of the environment (27 regions) at a scale of 1 : 50,000 in the sense of the amended Directive no. 1/2000-3 of Ministry of Environment of the Slovak Republic.

Although the above-mentioned advanced interpretational procedures have made a significant difference in interpreting and visualizing the results of field measurements of GS, they were still time consuming at the level

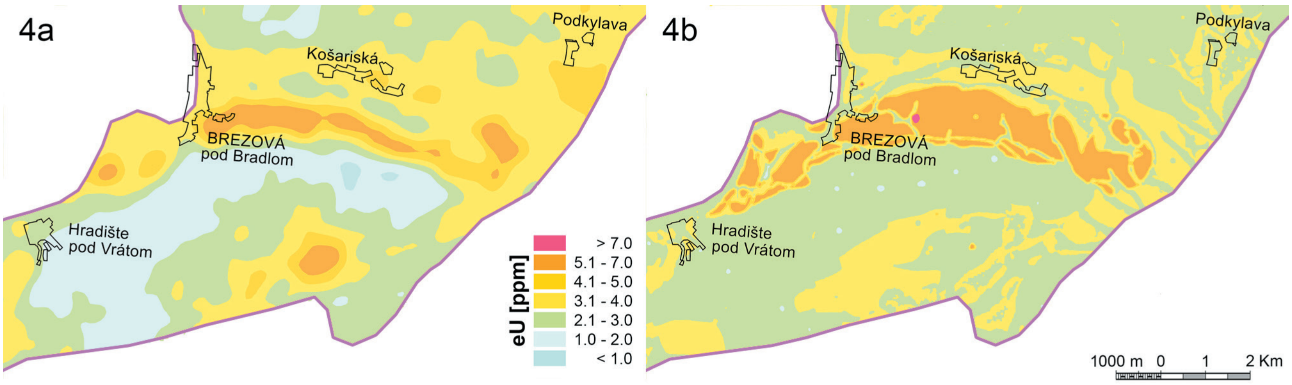


Fig. 2.4 *The options for processing and visualizing GS measurements by standard (4a) and new advanced (4b) interpretation techniques*

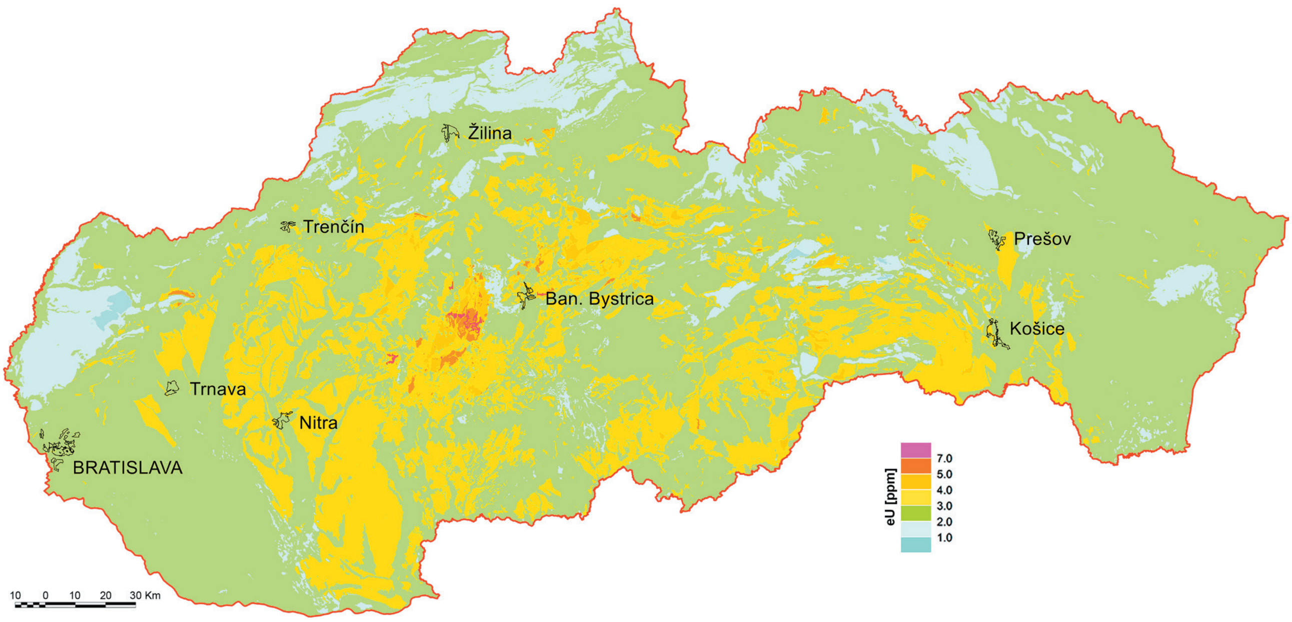


Fig. 2.5 *Concentrations of equivalent uranium eU [ppm] at the SR territory*

of "manual" interpretation. In the period of significantly higher data volume (39,396 objects) and the extent of the area coverage of the territory of Slovakia (about 2/3 of the state's area), the estimated workload would be considerably higher than the Department of Geophysics staff capacities. It was therefore necessary to design and implement as much as possible automated, computer-generated interpretation and visualization techniques.

2.3.1 Methodology and results of realized works

The processing itself took place in the MicroStation – Bentley graphical CAD/GIS software environment and in the Access database (MS Office) environment. The procedure and sequence of processing can be divided into four main parts.

The content of the first part of the processing was the modification and optimization of the digital geological map (Káčer et al., 2005) in the evaluated area. Its purpose was to increase the effectiveness of the subsequent evaluation but, above all, to interpret and clarify the results, to organize its structure. It was mainly about the editing of areas of geological units – the joining of small, for a given purpose, separately insignificant units into larger units, or on the contrary – the division of large areas into smaller units, taking into account the tectonic elements in this modification. From the resulting vector file as a graphical basis of the whole processing, a linked database of geological units (polygons) was created.

In the second part of the process, the main calculation of the evaluation of monitored parameters of natural radioactivity was carried out. In the first step, measurements were localized on the territory of the geological unit, in its immediate surroundings (up to 100 m from the outer boundary of the complex). Parameters for each geological unit were then determined as their arithmetic mean. In the second step, these values were modified according to the number of measurements in the area of the unit. For less than 1 object per 1 km^2, supplementary results with replacement parameter values for the type (geological index) were used. Further refinement of the evaluated parameters was carried out, which took into account the specific properties of some geological units – possible anthropogenic influences, unusual sampling conditions, detected systematic error of measurement results, etc.

The third part of the processing was the creation of a partition map for each of the parameters K, eU, eTh, eUt and Da. From the measurements database, the distribution maps of the measured objects were generated, which allowed the initial reading of the measured values. The main result of the processing is the area distribution maps according to geological units.

All resulting maps are created in the form of GIS, which allows to view the database parameters of individual geological units – polygons (e.g. the resulting average values and number of measurements per site, area, geological indices), or of individual point measurements directly from the graphical vector file environment. The final processing phase is a map of anomalous values, which shows the areas of detected anomalies of all monitored parameters in a specific map.

The last, fourth part of the processing is of a technical nature and its purpose was to create a digital base for exporting processed results to other graphic softwares. Numeric grids (25 x 25 m) were generated for all monitored parameters.

The final phase of the solution was the verification of the generated maps by the geophysicist – solver, in which the final detailed inspection of the output documents was carried out, measurement results not corresponding to the local geological structure, etc. The resulting data files were then processed and visualized in graphical softwares GIS/CAD products Oasis montaj and MicroStation (Figure 2. 6).

GAMMA SPECTROMETRY – ARTIFICIAL RADIOACTIVITY

Negative factors that have affected the population since the middle of the last century include undoubtedly artificial (induced) radioactivity – a product of military-industrial activity that significantly influences the overall radiation level of the environment.

The first artificial artefacts were registered in the biosphere after a series of US nuclear trials and bombardment of Hiroshima and Nagasaki in 1945. Nuclear explosions release a huge amount of energy, a portion of which is consumed for the production of unnatural (non-ionizing) radiation, but also to the emergence of a whole range of radionuclides, which condition the biosphere contamination.

Significant share of global environmental contamination by artificial radionuclides (in the long run, mainly ^{137}Cs) also have nuclear facilities accidents, as witnessed by a massive industrial accident at the Chernobyl nuclear power plant in April 1986. During the destruction of the nuclear reactor no. 4, large amounts of radioactive substances with an activity of 30–50 million curie (1 Ci = 3.7 x 10^{10} Bq), some of which were deposited on the territory of Slovakia (Gluch et al., 2005), were released.

In the first phase of the fallout, increased radioactivity was caused by radionuclides with a short half-life: ^{131}I (half life $T_{1/2}$ = 8 days), ^{132}Te ($T_{1/2}$ = 2.4 hours), ^{140}Ba ($T_{1/2}$ = 12.8 days), ^{140}La ($T_{1/2}$ = 10.4 hours), ^{99}Mo ($T_{1/2}$ = 2.8 days), ^{99}Tc ($T_{1/2}$ = 6 hours), ^{239}Np ($T_{1/2}$ = 2.33 days).

In the second phase, during which the territory of Slovakia was also contaminated, radionuclides with a longer half-life were responsible for radioactive pollution: ^{137}Cs ($T_{1/2}$ = 30 years), ^{134}Cs ($T_{1/2}$ = 2.3 years), ^{103}Ru ($T_{1/2}$ = 45 days), ^{106}Ru ($T_{1/2}$ = 1 years), ^{95}Nb ($T_{1/2}$ = 35 days), ^{90}Sr ($T_{1/2}$ = 28 years).

At the contact with Earth's surface ^{137}Cs is adsorbed by fine clay soil particles. Its mobility in soil depends on the amount and type of clay particles, the carbonate content, the humus and the pH of the soil cover. It is immobilized in soils with a low content of organic matter at a pH in the range of 4–7, with the dominance of muddy clay minerals. On the grassy areas, the bulk of ^{137}Cs is concentrated in the top 5–15 cm. Its concentration with depth decreases exponentially, almost without translocation by physico-chemical processes. Subsequent redistribution of ^{137}Cs is therefore linked to erosion, transport and accumulation of sediments, but not to transport in solution.

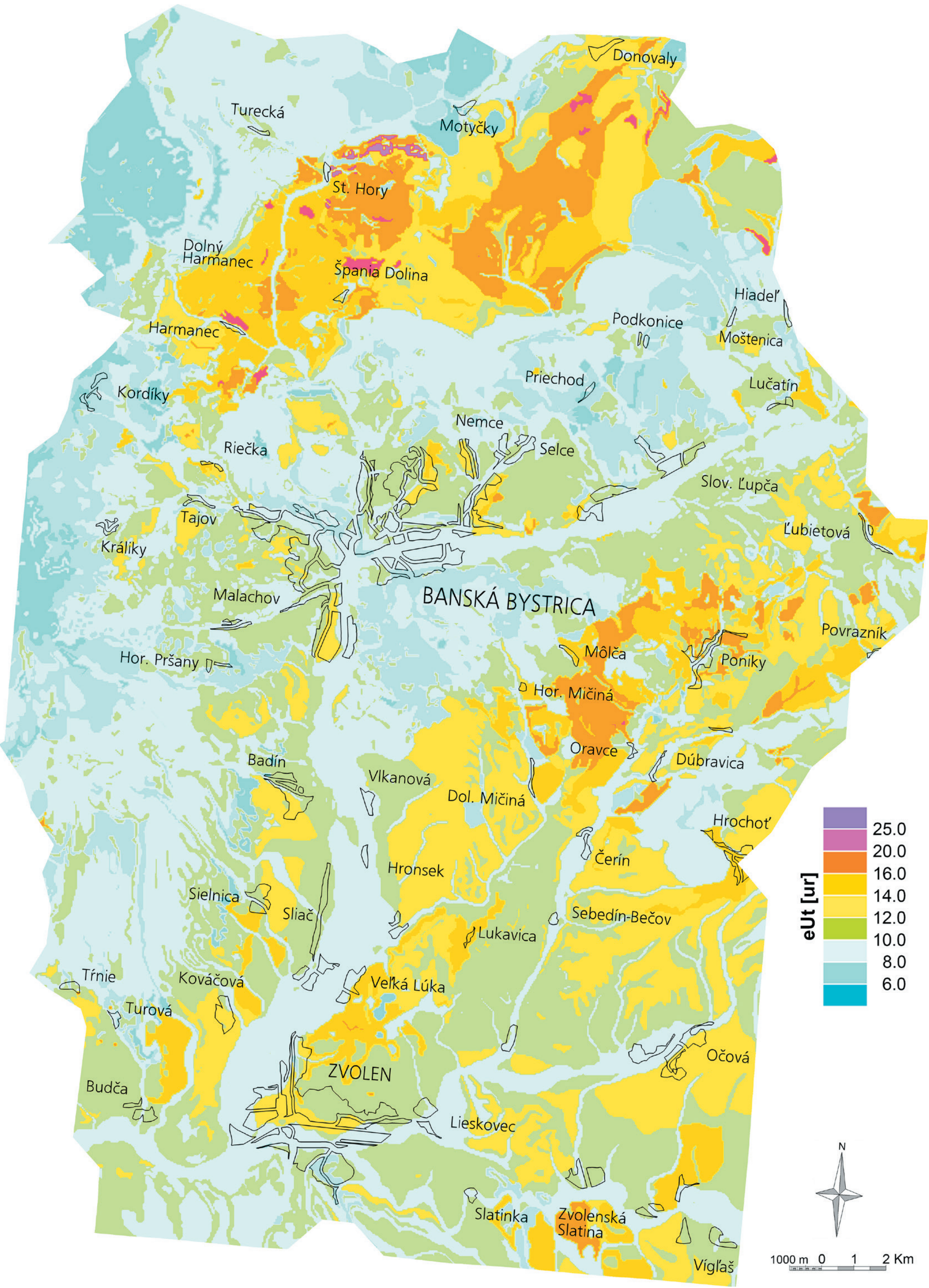


***Fig. 2.6** Total natural radioactivity eUt [ur], region Banská Bystrica – Zvolen*

The impact of radioactive fallout on the human organism can be predicted in several areas – direct irradiation of the organism, inhalation of radioactive air and intake of food with higher content of radionuclides.

After the completion of field geophysical works, the task of “Upgrade of Radioactivity Maps ^{137}C on the territory of Slovakia at 1 : 200,000 and 1 : 500,000” (Gluch et al.,, 2005) was set up by the Ministry of Environment (MoE SR) to draw up the required maps from all available relevant determinations of isotopic activity ^{137}Cs from the whole territory of SR.

2.4 Methodology and results of realized works

Artificial radioactivity parameters (activity ^{137}Cs) were measured by field gamma spectrometers (predominantly GS-256/GS-512 apparatus), concurrent with the concentrations of native radionuclides. There was measured outside urban agglomerations, or agricultural land used, directly at the surface, in places without or with only slight vegetation coverage, at measuring geometry 2π and measurement time-span 6 min. The additional energy spectrometer (ROI) was set to register ^{137}Cs (662 keV) gamma radiation. The conversion of measured pulses from the supplementary window to ^{137}Cs spatial activities was performed using calibration equations calculated from the results of laboratory assays of ^{137}Cs in samples taken from local deposits.

The basis for making upgraded maps provided the results of measurements by terrestrial gamma spectrometry at a scale of 1 : 200,000 with a density of 1 point per 10 km^2 (Daniel et al., 1999) of the whole territory of Slovakia (4,946 objects).

However, all available test results (Figure 2. 7) have not been incorporated in the maps prepared to address the above task and the outputs have not been converted to a uniform radio-geochemical level to a suitably chosen reference date. It was also necessary to convert a relatively large number of relevant documents into digital form from archive primary documentation (field logs and maps), or from the available graphical data (e.g. aerial measurements from the so-called "Great Bratislava" region). The data obtained became the essential database for the construction of the respective maps based on CAD/GIS products MicroStation and Oasis montaj.

The maps of the ^{137}Cs spatial activity (Figure 2. 8) illustrate the status of contamination of the territory of Slovakia with this radioisotope referring to the reference date 01.01.2005. All available results of ^{137}Cs activity determination from the entire territory of the SR for the period of 1990 to 2003 were used (19,791 objects, including the results of digitized aerial measurements).

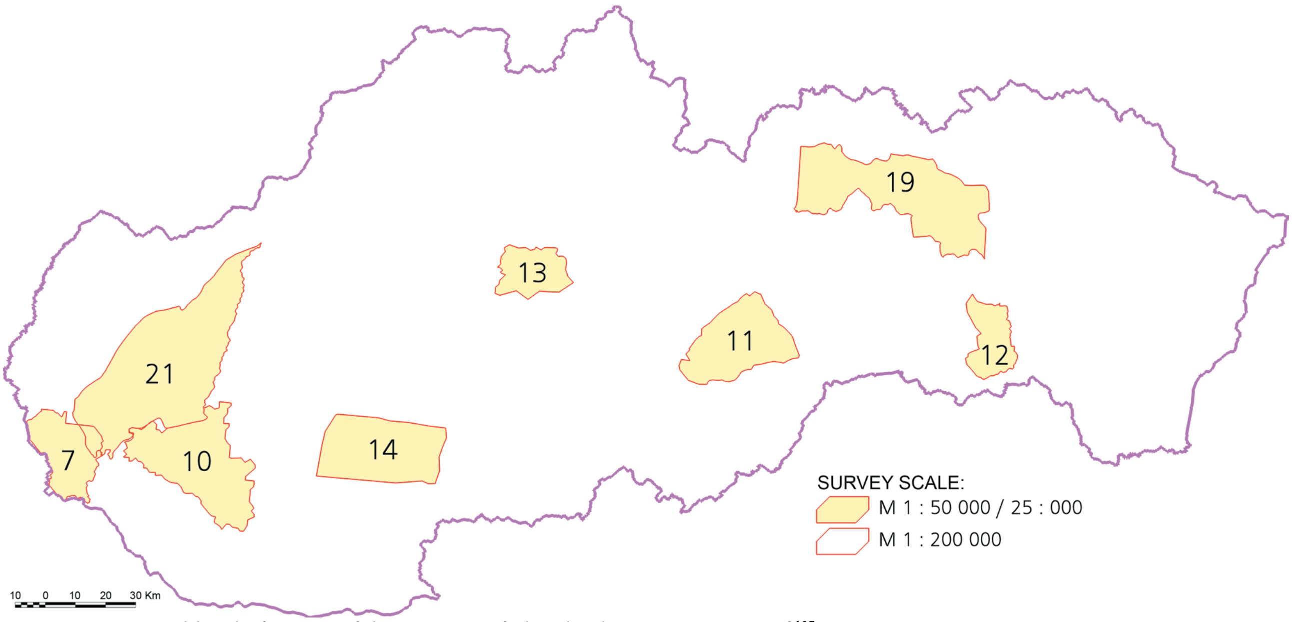


Fig. 2.7 *Regional level of survey of the territory of Slovakia by measurements of ^{137}Cs activity*
Regions – **7:** Great Bratislava (airborne measurements); **10:** Galanta; **11:** Jelšava – Lubeník – Hnúšťa; **12:** Košice – City; **13:** Banská Bystrica – Zvolen; **14:** Levice – Mochovce; **19:** Poprad and Upper Torysa catchments; **21:** Trnavská pahorkatina Upland

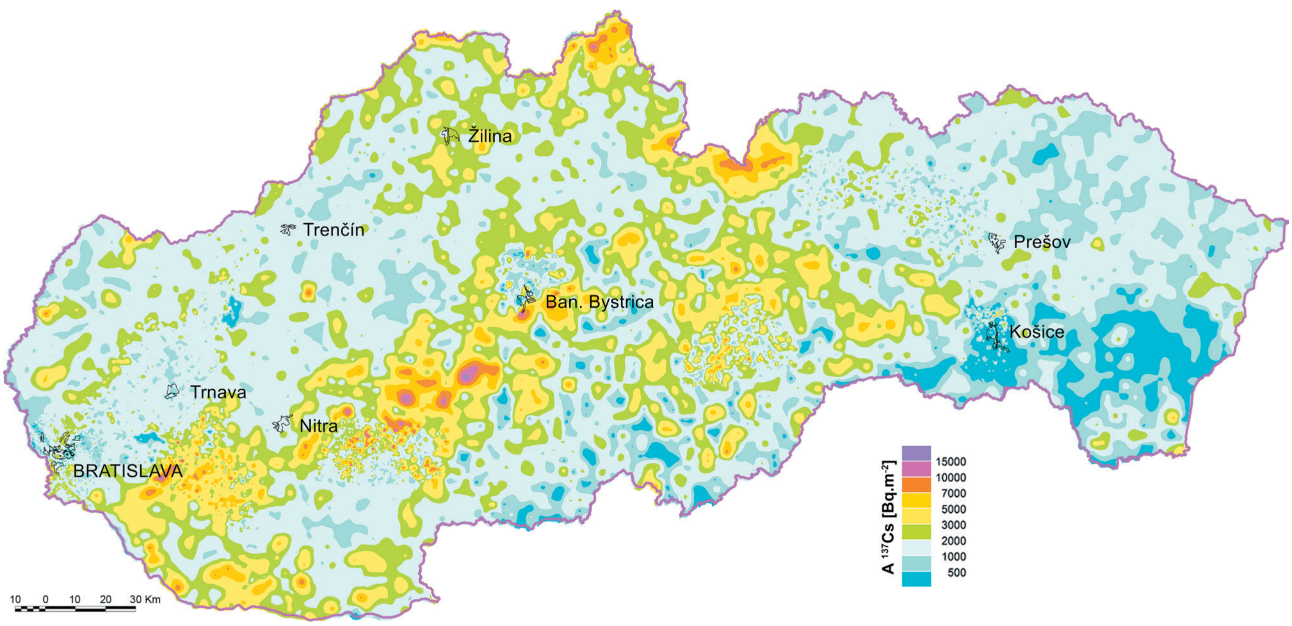


Fig. 2. 8 *Spatial ^{137}Cs activity in the territory of the Slovak Republic*

The distribution of the ^{137}Cs spatial activity values in Slovakia is significantly different. The low activity is concentrated in the east, in the central part of the south of Slovakia and on the west of the Slovak Republic in the wider area of Váh and Nitra rivers. The distinctly lowest levels of spatial activity (below 0.5 $kBq.m^{-2}$) are in the areas of Východoslovenská nížina Lowland, Košice Basin and Slanské vrchy Mts.

Increased activity (above 3.0 $kBq.m^{-2}$) was recorded in the 40 km wide band of the NE-SW direction, covering the area of the Vysoké and Nízke Tatry Mts., Štiavnické vrchy, Pohronský Inovec, Podunajská pahorkatina Upland and Podunajská nížina Lowland in wide area of Galanta and Dunajská Streda. In this zone – the highest spatial activities of ^{137}Cs were recorded in Banská Štiavnica (18.1 $kBq.m^{-2}$), Nový Tekov (28.7 $kBq.m^{-2}$) and Košúty (23.1 $kBq.m^{-2}$) within the territory of Slovakia (Gluch et al., 2005).

In terms of the Decree 12/2001 of the Ministry of Health SR on the Requirements for Radiation Protection, the level of intervention for radionuclide ^{137}Cs (after radioactive cloud passage after radiation accident for contamination of water and grazing for dairy production) is derived at the level of 10 $kBq.m^{-2}$. Such results were measured only on a point-by-point basis in small areas in the western and central Slovakia. The intervention level for permanent population resettlement (10,000 $kBq.m^{-2}$) was not recorded in the SR within these measurements.

RADIOMETRY – EMANATION MEASUREMENTS MAPS OF RADON RISK FORECASTS

Radiometric methods, including so-called emanation measurements (radon survey) were used in former Czechoslovakia since the second half of the 1940s, especially when searching for and exploring radioactive raw materials. The assessment of the impact of natural radioactivity on the population was not investigated or evaluated during that period and neither it was the subject of interest of the relevant state institutions.

Since the beginning of the 1990s, specialists of the SGIDŠ have solved a number of geological tasks for the Ministry of the Environment, including research on natural radioactivity of the territory of the Slovak Republic and one of the outputs were regional maps of the radon risk.

2.4.1 Radioactivity of ground air

Radioactivity of the ground air causes radioactive gases (emanations) resulting from the disintegration of uranium and thorium in the rocks, especially the radon ^{222}Rn. Its dominant sources are mainly rocks with an increased content of radium ^{226}Ra. In general, radon content in ground air depends mainly on radium content in rock, gas permeability and tectonic disintegration of the rock environment and complementary climatic and meteorological factors (humidity, temperature, pressure, ...).

Radioactive gas radon has three isotopes:

- actinon – ^{219}Rn (half-life of 3.9 seconds), is generated in the actinium decay series ^{235}U,
- thoron – ^{220}Rn (half-life 54 s), is a fission product of ^{232}Th in the thorium decay series,
- radon – ^{222}Rn (half-life of 3.825 days), resulting in the conversion of ^{238}U in the uranium series.

Due to the very short half-lives of actinon and thoron, radon ^{222}Rn (decay product ^{226}Ra) has a dominant radiation impact in the ground air. Radon has a higher density than air (it is the heaviest gas in nature), is well soluble in water and even better in organic fluids (crude oil, oil), it is colourless, tasteless and odourless. It is well adsorbed by coal (but also on paraffin and rubber) and in the natural environment, on the clays. Solubility and adsorption of radon increases with decreasing ambient temperature.

Radon easily penetrates the rock environment by diffusion and convection. The main source of natural radon is the geological environment, i.e. some minerals and rocks, but also groundwater flowing through rocks with increased uranium content. Due to the half-life of the maternal elements (^{238}U ~ 4.5 billion years, ^{226}Ra ~ 1,600 years), the geological environment ensures its permanent supply.

Radon has significant migratory properties and its contents in soil air and water are not stable. They depend not only on radium concentrations in the rock but also on other factors affecting its propagation (meteorological conditions – humidity, temperature, pressure, wind velocity, gas permeability – porosity, tectonic rocks, etc.).

The most significant manifestation of convection is in tectonically disturbed zones and failures and in areas with a high coefficient of diffusion (scree, porous rocks). Radon transport by convection is radically higher than by diffusion and therefore anomalous concentrations may indicate tectonics, mylonitization zones, and disintegration of the rocks, which are good communication paths for gases.

Concentrations of radon in rocks generally do not exceed 30 $kBq.m^{-3}$. In the open air it is rapidly diluted with atmospheric air and its concentration is about three times lower than in the rocks (Iglárová et al., 2011).

2.4.2 Methodology and results of realized works

The basis for the compilation of regional maps of radon risk forecast are the results of measurements of the radon ^{222}Rn volume activity in ground air (RVA) on reference areas (RAs).

The RAs of the radon survey were arranged with a density of 1 RA per 10 km^2, preferably out or within town residential areas, taking into account the availability and type, or the thickness of the sedimentary cover.

All necessary procedures – fieldwork methodology, sampling of RVA in soil air, calculation method, determination of gas permeability of local soils and rocks, determination of radon risk of RA, etc. – we report in the paper 4 (Monitoring the volumetric activity of radon in the geological environment of the Slovak Republic), published in this issue of SGM.

2.4.3 Geological Information System – GeoIS

An important geological task, in which the results of RVA measurements in ground air in the Slovak Republic have been thoroughly evaluated and processed, is the project of "Geological Information System – GeoIS" (Káčer et al., 2014).

The RVA measurements in the ground air were financed from the state budget for the purpose of compiling the derived, forecast maps of radon risk. On the territory of Slovakia, a significant number of measurements (9,288 RAs, i.e. more than 170,000 individual probes) in the last three decades at various scales, from the scale of 1 : 200,000 up to a detailed survey at scale 1: 1,000, were carried out (Figure 2. 9). The results are archived in the geophysical database of SGIDŠ. The aim of this task was to elaborate regional maps of radon risk forecast at scales of 1 : 500,000 to 1 : 50,000 in accordance with the amended Directive no. 1/2000-3. of the Ministry of Environment of the Slovak Republic

Output maps at 1 : 500,000, or 1 : 200,000 (Figure 2. 10) were constructed on the basis of the "General Geological Map of the Slovak Republic at 1 : 200,000" (Bezák et al., 2008), or "Digital Geological Map at scale 1 : 50,000" (Káčer et al., 2005). They were constructed according to the methodology used in the creation of natural radioactivity maps (Figure 2. 11). All available relevant base documents, data and sources of information (structural-geological, hydrogeological, engineering geological, as well as archive radiometric data) from the geophysical database of SGIDŠ were also incorporated.

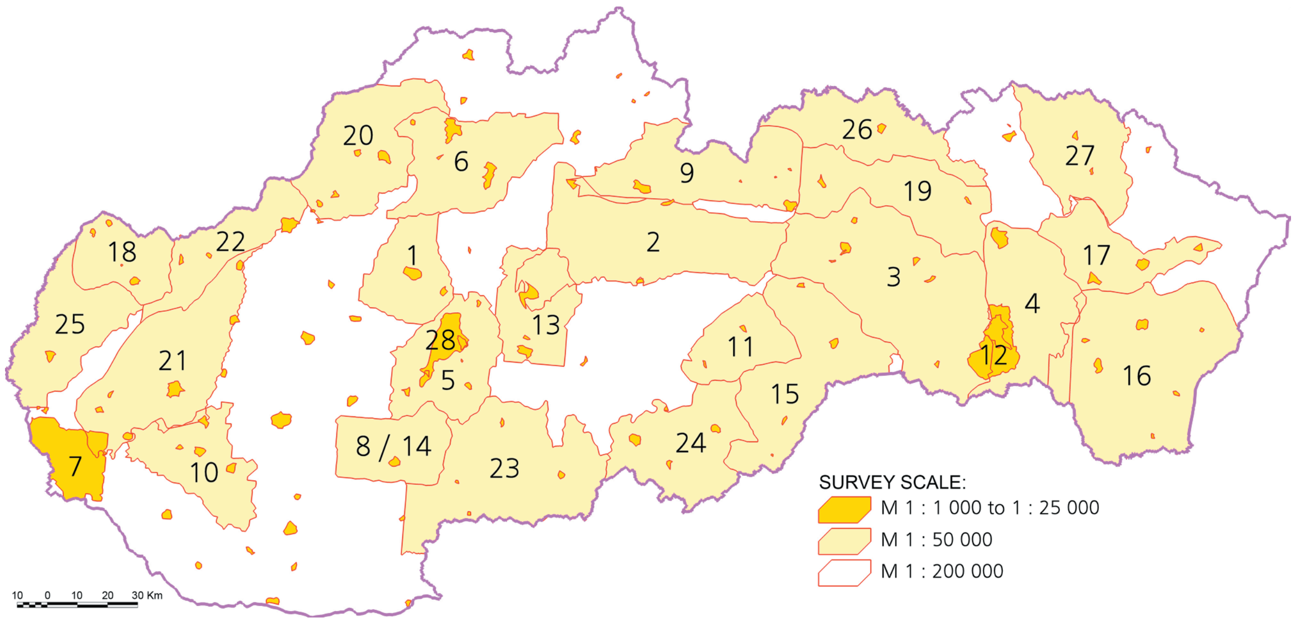
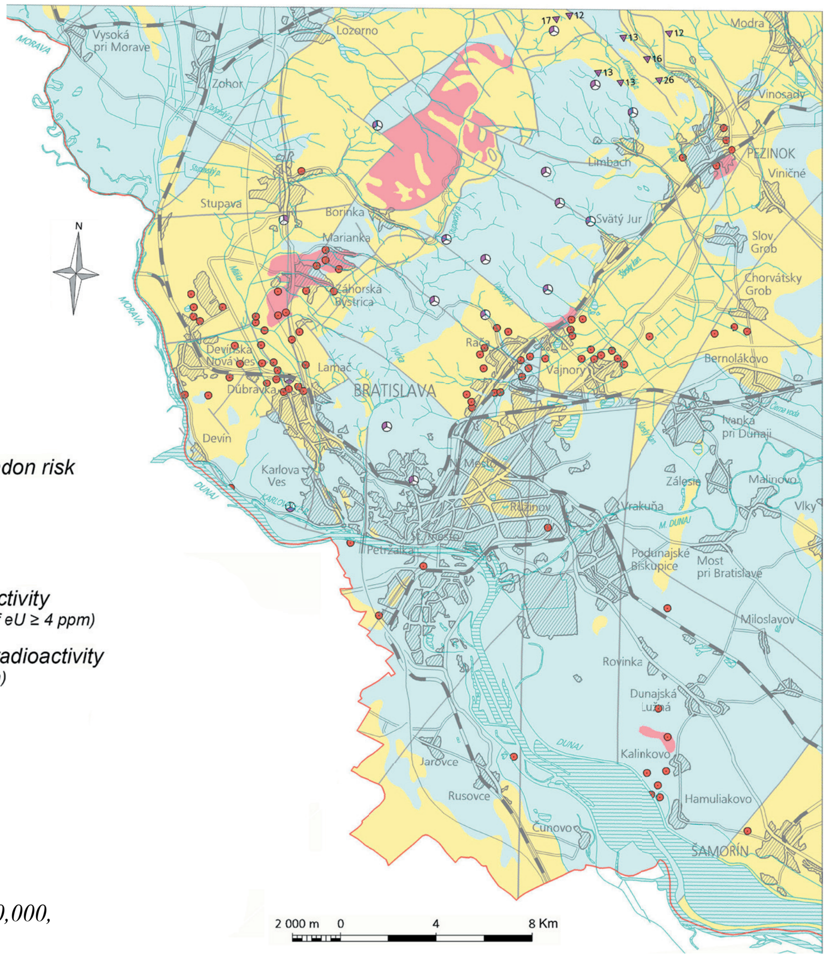


Fig. 2.9 Regional survey of the territory of Slovakia by radon survey
Regions – **1:** Horná Nitra region; **2:** Nízke Tatry Mts., Starohorské vrchy Mts., Bystrická vrchovina Upland, Čierťaž; **3:** Hornádska kotlina Basin and E part of the Slovenské rudohorie Mts.; **4:** Košická kotlina Basin and Slanské vrchy Mts.; **5:** Žiarska kotlina Basin and Banská-Štiavnica region; **6:** Malá Fatra Mts. and parts of the adjacent basins; **7:** Great Bratislava; **8:** NE part of the Levice District; **9:** Vysoké Tatry Mts. and Liptovský Mikuláš – Ružomberok; **10:** Galanta; **11:** Jelšava – Lubeník – Hnúšťa; **12:** Košice – City; **13:** Banská Bystrica – Zvolen; **14:** Levice – Mochovce; **15:** Slaná catchment in the Rožňava District; **16:** TIBREG; **17:** Vranov nad Topľou – Humenné – Strážske; **18:** Chvojnická pahorkatina Upland; **19:** Poprad and Upper Torysa catchmens; **20:** Middle Váh River catchment; **21:** Trnavská pahorkatina Upland; **22:** Myjavská pahorkatina Upland and Biele Karpaty Mts.; **23:** IPREG; **24:** Lučenská and Rimavská kotlina basins; **25:** Záhorská nížina Lowland; **26:** Ľubovnianska vrchovina Upland; **27:** Ondavská vrchovina Upland; **28:** Žiarska kotlina Basin



NOTES:

Radon risk:

- high
- moderate
- low

single object (reference area) in high radon risk

Prognosis of elevated radon risk:

- along the tectonic lines
- in areas with increased natural radioactivity (delimitation of a territory with a concentration of eU ≥ 4 ppm)
- ▽17 in the vicinity of anomalies of natural radioactivity (position and value of anomaly with eU ≥ 10 ppm)
- in areas of groundwater sources with increased natural radioactivity:
  - concentration $U_{nat} \geq 0.050$ mg.l^{-1}
  - volume activity $^{226}Ra \geq 0.2$ Bq.l^{-1}
  - volume activity $^{222}Rn \geq 50$ Bq.l^{-1}

Fig. 2.10 *Radon risk forecast map, scale 1 : 200,000, sheet 44 – Bratislava*

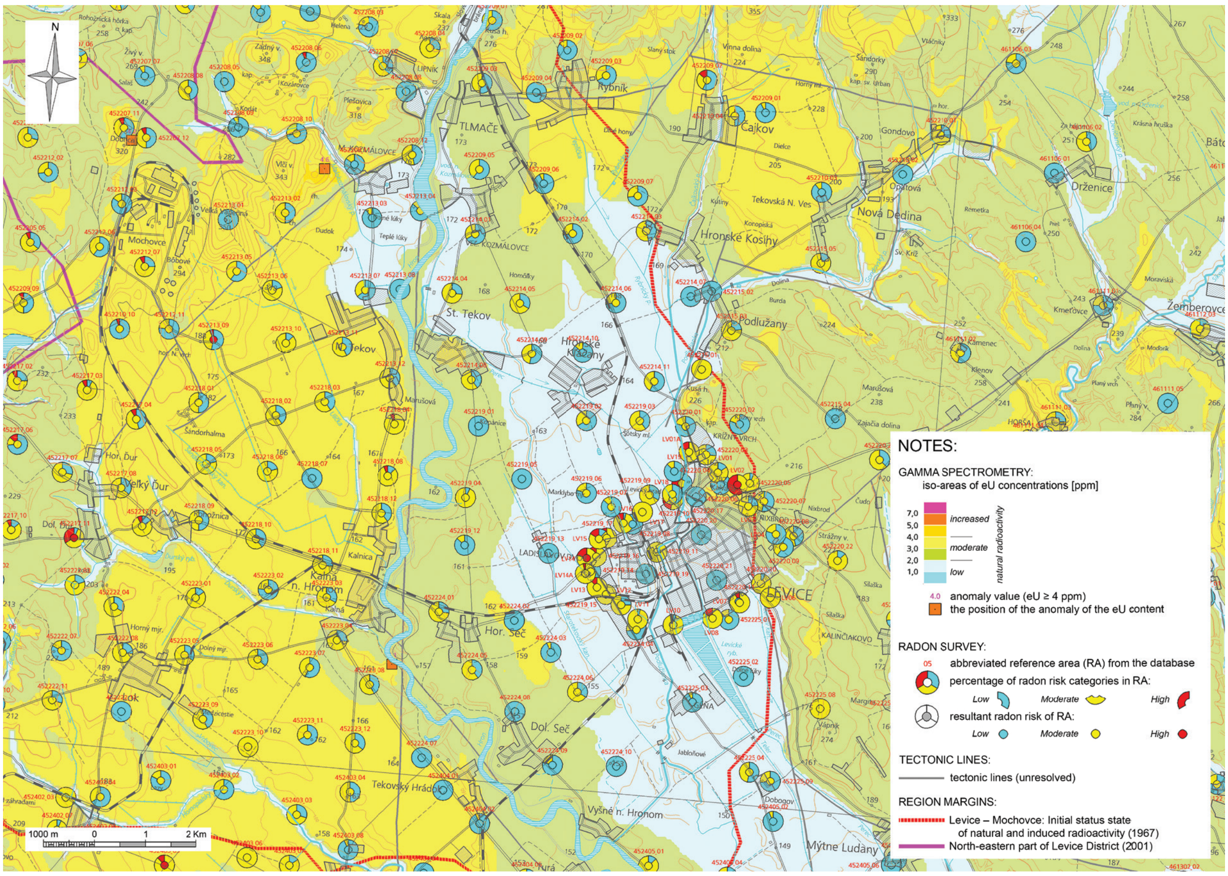


Fig. 2.11 *Summary map of radon risk and concentration projections [ppm], Levice – Mochovce, scale 1 : 50,000 (cut, reduced)*

Conclusions

Natural but also artificial – induced radioactivity is an integral part of the environment of the human population. The entire biosphere has evolved since its inception in the natural field, and since the half of the last century it has also been induced by artificial radioactive radiation. In terms of the potential risk of exposure of the population by irradiation from both natural and artificial sources, some radionuclides, contained in the geological environment (rocks, water, atmosphere), are significant. Their distribution in the environment has to be reviewed, documented and evaluated.

All current relevant knowledge of natural and induced radioactivity in individual environmental compartments and their deterministic effects have confirmed the dominant importance of natural radiation sources to the global average of the radiation burden of the population. For the future, it is therefore necessary to carry out research work and scientific studies aimed at estimating the radiation burden of the population as much as possible.

The contribution of SGIDŠ as an organization ensuring the performance of the State Geological Service of the Slovak Republic in the exploration and evaluation of geological factors of the environment is irreplaceable and undeniable. The purpose of this article was to summarize the share and input of the Department of Geophysics at the SGIDŠ for more than two decades since its inception; from the beginning of a relatively simplified approach, conditioned by technical and methodological capacities in the period of its creation, to advanced sophisticated geological and geophysical information systems at present.

he public is familiarized with the results of the works, which are widely available on the Internet through well-designed user interfaces, allowing interactive access to individual relational databases, as well as graphical, table and text outputs of solved tasks. The authors of this article also wanted to make available some of the less well-known working practices of applied geophysics used in the geological practice of SGIDŠ in recent years.

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SR Government Regulation No 350/2006 laying down detailed rules for the protection of the environment from exposure to natural radiation.

STN 73 1001 Geotechnical constructions. Foundation of buildings.

Slovak Geol. Mag., 17, 2 (2017), 25 – 48

3. Map of Magnetic Anomalies at the Territory of Slovakia and Their Interpretation

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Abstract: The Unified Geomagnetic Map of Slovakia, compiled in 2008, has become the basic map for the interpretation of the sources of magnetic anomalies in the territory of the Slovak Republic. The latest geophysical software Oasis montaj was used to interpret and model magnetic anomalies. The results of the interpretation and modelling of magnetic anomalies provide the basis for geological and tectonic affiliation and petrographic classification of their sources. On the basis of the results obtained, maps of the spatial extent of sources of magnetic anomalies in the pre-Tertiary formations and products of Tertiary and Quaternary volcanism in our territory were compiled. The latest geomagnetic measurements have also revealed the buried volcanoes in various regions of Slovakia, the various types of granitoids (tonalites) and the extensive dimensions of Vepor Stratovolcano have also been distinguished.

Keywords: magnetometry, geomagnetic field of the Earth, magnetic map of Slovakia, geophysical information system SGIDŠ, interpretation of geomagnetic anomalies

3.1 Introduction

Terrestrial geomagnetic measurements of the vertical component of the total intensity of the Earth's magnetic field were made in the 1960s in Eastern Slovakia and in the "Little Podunajská nížina Lowland". In the 70s of the previous century, exploration continued in the Spišsko-gemerské rudohorie Mts., the Ipeľská kotlina Basin and Krupinská vrchovina Upland, the Lučenská and Rimavská kotlina basins, and later in the Spišsko-gemerské rudohorie Mts., the Slovenské rudohorie Mts. and the eastern part of the Nízke Tatry Mts. After evaluating the results of the ground geomagnetic survey, the aeromagnetic mapping of selected areas of Slovakia continued. Until 1992, the territory of Slovakia was covered by geomagnetic measurements by various technological procedures and different instrumentation that responded to the given period. By airborne magnetometry, about 2/3 of the Slovak territory was measured. In the years 2005–2008 the territories without any coverage were complemented by terrestrial geomagnetic mapping with a step of 1–3 points/km^2 (Kubeš, 2008). As they were predominantly mountainous areas, the number of points per km^2 was limited by the terrain. The total magnetic induction vector T was measured. From the geomagnetic data thus obtained, a unified magnetic map of Slovakia (Figure 3.1) and a magnetic database with a grid of 125 x 125 m were compiled.

The detected magnetic field anomalies were gradually interpreted by various authors and various interpretive techniques that were constantly evolving. Many times, however, the known magnetic properties of rocks in some regions were not interpreted and modelled many times, or there was a lack of knowledge of these properties. Sometimes, even the latest knowledge of the geological setting

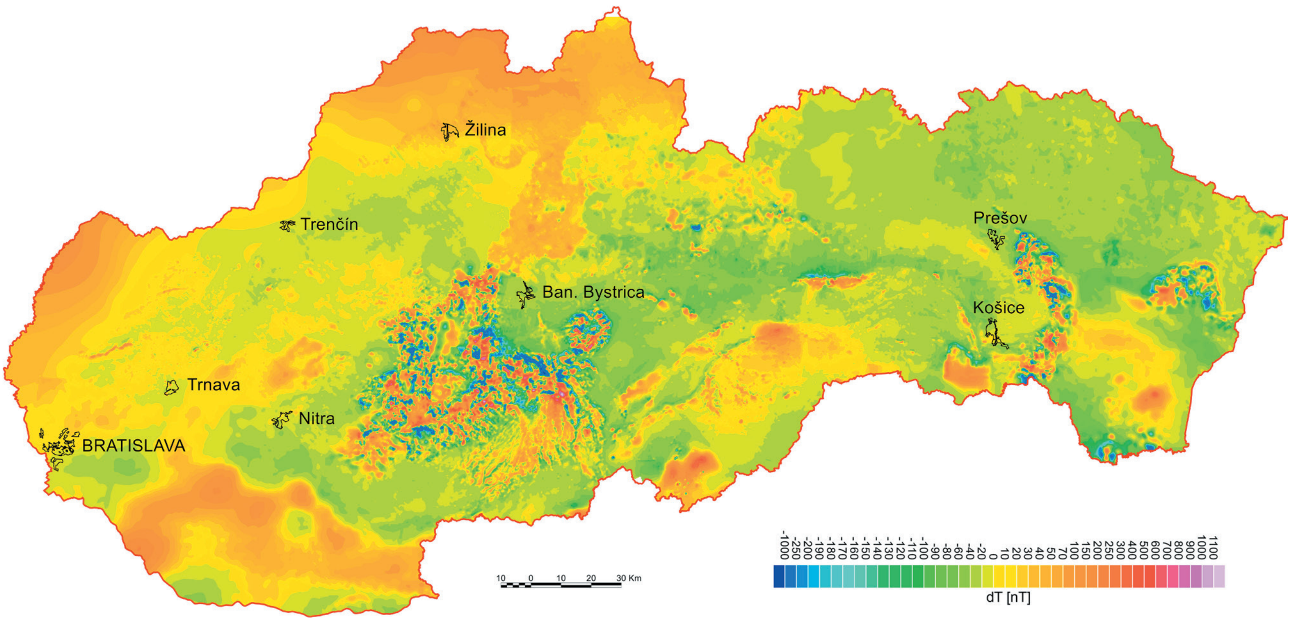

Fig. 3.1 *Unified magnetic map of the territory of Slovakia*

of Slovakia has not been reflected, which in many cases has led to erroneous interpretations. In interpreting sources of magnetic anomalies from Tertiary or Quaternary volcanism, the situation was also complicated by the existence of rocks with normal and reversed magnetic polarization.

3.2 General characteristic of the Earth's geomagnetic field

3.2.1 Earth's geomagnetic field

Earth's magnetic field study is one of the oldest scientific disciplines. The theory of the Earth's magnetic field depended on the technical achievements and the development of the mathematical apparatus at that time. The first mathematical expression of the earthly geomagnetic field was already presented by Gauss in 1838. Realistic ideas of the emergence of the Earth's magnetic field began to emerge after 1940. One of the most famous theories was developed by E. Bullard (1949) and W. Elsasser. The Bullard model is based on the construction of a body of the earth, the inner core of which is solid and the outer is composed of molten iron, nickel and a small silicate admixture. As a result of the upward and downward movements in the Earth's core and the forces resulting from the rotation of the Earth, the inner layers of the molten core rotate faster than the extern ones. The Earth's mantle rotates faster than its adjacent core layers. Then, Bullard explains the Earth's geomagnetic field as the reflection of all movements and interactions between electromagnetic and mechanical forces. Although this theory is mathematically deeply elaborated and illustrates the emergence of the major dipole magnetic field, the secular variations and continental magnetic anomalies as well as the Western drift, it does not explain the origin of the inversion of the Earth's magnetic field. Experts have suggested a whole bunch of other models, however, they can only be considered as partial solutions to some specific issues of the Earth's magnetic field. Previous knowledge does not make it possible to fully elucidate all the complexities of the geomagnetic field and to verify the ideas about composition and the processes that are taking place there.

3.2.2 Components of the Earth's magnetic field

The Earth's magnetic field at a certain point on the Earth's surface is determined by a vector of magnetic induction (T), which can be decomposed to the vertical (Z) and the horizontal component (H). We can also express the vector T by means of directional parameters, namely magnetic declination (D) and magnetic dip (I). Magnetic declination is the angle between the geographic meridian and the horizontal component H falling in the direction of the magnetic meridian. Dip (inclination) is the angle that generates the total vector T with a horizontal plane (H). Declination can be 0 to 180º (East or West). The dip increases towards the magnetic poles, where it has a value of 90º (in the north + in the south -). The magnitude of the vector of magnetic induction T is about 48,000 nT, dip +65º and declination to +5º.

3.2.3 Structure of the Earth's magnetic field

The resulting magnetic field of Earth consists of a permanent and time-varying magnetic field. The permanent field matches the sum of the effects from:

- the dipole field (the magnetic field of the homogeneously magnetized Earth body),
- the magnetic field of global, or continental anomalies (sources located in about half of the Earth's radius – probably core-mantle interface)
- the magnetic field of regional anomalies (sources are usually located in the upper parts of the Earth's Crust – to a depth of about 35 km);
- the magnetic field of local anomalies (sources are located closer to the surface).

Time variations of the Earth's magnetic field

Time changes of the Earth's geomagnetic field are caused by different sources and have a different duration. These time changes are mainly caused by:

- the processes that take place in the Earth's body (mainly in the Outer Core), so-called secular variations – lasting from a few dozen, hundreds up to hundreds of thousands of years. Their focal points are moving in different directions, mostly westward (drifting). During some geological periods there was an inversion of the Earth's magnetic field polarity with an average period of 400 to 600 thousand years;
- the processes going on in the Sun and in the Earth's atmosphere (they depend on the physical processes running on the surface of the Sun and the mutual position of the Earth and Sun or the Moon). The most important are annual and daily variations.

Magnetic properties of minerals and rocks

The magnetic properties of minerals are characterized by some parameters:

- magnetization and magnetic polarization – rocks with magnetic minerals are magnetized in the Earth's magnetic field. In the current magnetic field, rocks obtain the induced magnetization. Rocks can also obtain remanent magnetization, which depends not only on the magnetizing field, but also on other factors existing at a given time when the magnetic field has acted (temperature, chemical reactions, rotation of magnetic poles, etc.)
- magnetic susceptibility (F) and permeability (P) – are dimensionless quantities that characterize magnetic substances (diamagnetic, paramagnetic and ferromagnetic),
- Curie temperature Tc – magnetic susceptibility (or permeability) and magnetization (or magnetic polarization) are temperature dependent. It is the temperature where magnetic substances lose their magnetic properties. Magnetite +578 ºC, hematite and maghemite +675 ºC, pyrrhotite +300 to +325 ºC,
- The temperature (point) of the TT transition – by cooling (e.g. with liquid nitrogen -196 ºC), the magnetic substances become non-magnetic. When reheated, the so-called "magnetic memory" appears; e.g. of hematite when reheated above -23 ºC.

Magnetic properties of rocks depend on the amount of magnetic minerals. The most important magnetic minerals are: magnetite, ulvöspinel, maghemite, hematite, ilmenite and pyrrhotite.

According to the magnitude of the magnetic susceptibility, we divide the rocks into:

- practically non-magnetic: below 300 x 10^{-6} of·SI units,
- very weak magnetic: 300 to 1,000 x 10^{-6} of·SI units,
- weakly magnetic: 1,000 to 10,000 x 10^{-6} of·SI units,
- magnetic: 10,000 to 50,000 x 10^{-6}· of·SI units,
- strongly magnetic: over 50,000 x 10^{-6} of·SI units.

The highest magnetic susceptibility, as well as the natural remanent magnetization, have the magnetite-containing rocks. These are, in particular, the igneous and metamorphic rocks. The lowest magnetic susceptibility have the sedimentary rocks containing hematite.

3.2.4 Magnetic anomalies

Magnetic field anomalies are detected in areas where the measured magnetic field is significantly different from the calculated normal Earth field. They are characterized by a significant change in Earth magnetic field gradients. While the normal field gradient is several nT/km, the gradient of the measured field reaches several tens to hundreds nT/km. The magnitude of the *normal magnetic field* depends on the geographical coordinates and in the past it was determined differently for different epochs and regions, making it impossible to build magnetic maps, for example, for Central Europe. At present, the so-called the International Geomagnetic Reference Field (IGRF) has been adopted, whose calculation is already the basic tool of modern geophysical software.

The magnitude and shape of magnetic anomalies depends on the dimensions (depth of the upper and lower edges of the body, thickness, etc.), structural conditions (dip, magnetic effect from several sources) and magnetic properties of rocks (magnetic susceptibility or direction and magnitude of the magnetization vector both induced and remanent). The subject of magnetic anomaly interpretation is the solution of direct, or inverse magnetometry.

3.3 Level of geomagnetic survey of Slovakia

The first aeromagnetic measurements in Slovakia began at the end of the 1950s at a scale of 1 : 200,000 (Mašín et al., 1963). The map of the isolines was compiled from profile measurements of the total magnetic field strength for a mean flight height of 100 m above the terrain at a profile distance of 2 km. Due to the low resolution of the devices used, the complex morphological conditions and the distance of the measured profiles, the maps are not suitable for further use. Moreover, the measured data does not exist in digital form.

Experimental aeromagnetic measurements at higher altitudes were made in 1966 for a flight height of 500 m above the ground and 2,000 m above sea level in the Central Slovakian Neovolcanites and 300 m above the terrain in the East Slovakian Neovolcanites (Šalanský, 1970, Beneš, 1971). The measured data are also not in digital format.

In the period of 1976 and 1992, the interior of the Western Carpathians was air-mapped. The measured area does not include the Podunajská and Východoslovenská nížina Lowlands, Veľká Fatra, Chočské pohorie, Nízke and Vysoké Tatry mountain ranges and the whole area of the Outer (flysch) Carpathians. The total magnetic field T intensity vector was measured, with a flight height of 80 m above the relief of the terrain. The profile distance was 250 m with a measurement step of 25–55 m (Gnojek & Janák, 1986; Dědáček et al., 1991; Gnojek & Kubeš, 1991; Gnojek, Janák & Nemčok, 1992).

The terrestrial magnetic measurements began in eastern Slovakia in 1960 (Man, 1961). The vertical component of the total vector of the magnetic field with a density of 4–6 points per km^2 was measured.

The next ground geomagnetic measurements were carried out in 1962 in the Podunajská nížina Lowland. The vertical component of the magnetic field was measured with a density of 1 point/km^2 and the values were processed to a scale of 1 : 200,000 (Man, 1962).

Bárta commenced in 1962 the field magnetic measurements at a scale of 1 : 25,000. The vertical component of the magnetic field in the Spišsko-gemerské rudohorie Mts. region with a density of 10–12 points/km^2 was measured (Bárta, 1969).

In 1974 the area of Ipeľská and Krupinská vrchovina Highlands was the subject of measurement. Šefara et al. carried out field measurements of ΔZ at a scale of 1 : 25,000 with a density of 5–15 points per km^2 (Šefara et al., 1974).

In the Lučenská and Rimavská kotlina Basins measurements were carried out with a density of 10–12 points/km^2 in the years 1969–1970. The component of the Earth's total vector of the magnetic field with the output to the maps was 1 : 25,000 and 1 : 50,000 (Bodnár, 1979).

In 1980, Obernauer completed the ground measurement in the western part of the Slovenské rudohorie Mts. and in the eastern part of the Nízke Tatry Mts. with a density of 10–12 points per km^2 at a scale of 1 : 25,000. The partial component of the total vector of magnetic induction of the geomagnetic field and also the magnitude of the total vector T (Obernauer, 1980) and the wider area of Bratislava – Malé Karpaty area, SE part of Záhorská nížina Lowland and NW part of the Podunajská nížina Lowland were measured. Output maps contained the ΔT isolines at a scale of 1 : 25,000 (Bárta et al., 1988).

In 2005–2008, terrestrial magnetic mapping covered large areas of territories until then without any magnetic field measurements (Kubeš, 2008). Geographically, they fall (according to Mazúr and Lukniš, 1980) within: Bukovské vrchy Mts., Laborecká vrchovina Upland, Ondavská vrchovina Upland, Busov, Čergov and Beskydské predhorie Mts. The area of interest in the Inner Carpathians is located in the Žilina Region in the north of Slovakia. The region includes Skorušinské vrchy, Chočské vrchy, Veľká Fatra, Vysoké Tatry, Nízke Tatry Mts., Podtatranská kotlina Depression and Kozie chrbty Mts. Geomagnetic survey coverage is shown in Figure 3.2.

***Fig. 3.2** Geomagnetic survey coverage of the territory of Slovakia*

From previous measurements a database of geomagnetic measurements was created (Kubeš, 2008). For the creation of the database measurements were used in the sense of Table 3.1. Existing database of magnetometric data of Slovakia was compiled on the basis of airborne (Gnojek, 1986; Gnojek, 1991; Gnojek, 1992) and ground magnetometry outputs (Man, 1962; Možný, 1963; Man, 1961; Kubeš, 2008).

Basic data on aeromagnetic measurements

Airborne magnetometry in M 1 : 25,000 covers approximately 70% of the territory of the Slovak Republic. The base flight profiles were 250 m apart and 2,500 m perpendicular bridging profiles. Sampling of all measured values took place at a frequency of 1 sec. Flight height ranged from 70 to 100 m above terrain, at flight speeds around 120 to 130 km x hour^{-1}. Aircraft equipment was carried by helicopters (predominantly Mi-8) in all areas of neovolcanites, core mountains and intermountaineous depressions vessels, only in the southern part of the Východoslovenská panva Basin, in the Orava area and Levočské vrchy Mts. it was transported by biplane AN-2.

The entire volume of aviation magnetometry was measured by the proton magnetometer G-801/3B of the Company Geometrics (USA). When helicopters were used, the magnetometer detector was in the subframe, in the case of AN-2 aircraft, the detector was at the outer edge of the wing.

The bulk of aerial measurements (until 1982) were locally documented by a video record of the flight path by the Company Sony. Subsequent confrontation of a video with a detailed 1 : 25,000 topography map was then the basis for determining the point data of each flight profile. Only in the Juhoslovenská panva Basin, in the Orava area and Levočské vrchy Mts. was the location of the air data measured by Motorola's Mini Ranger III positioning system (USA). The terrain's flight height was measured by a radio shader with the same one-second frequency. The continuous recording of all data on board aircraft was digital.

In the processing of aviation magnetic data, correction was applied to daily variations of the geomagnetic field. These variations were largely measured by their own portable variation station, located in the airport, where the base of the measuring group was. Only in cases of natural magnetic field interference by electrified railways the values of daily variations were taken from the Geomagnetic Observatory in Hurbanovo. The actual calculation of the delta T anomalies was then carried out by reduction to the normal field, which was determined for the Carpathian part of the Czechoslovak Socialist Republic by O. Man to the epoch 1974, 3.

From the resultant values of the observed geophysical parameters – the ΔT anomalies obtained along the individual flight paths, a regular square network of 125 m x 125 m dimensions was formed mathematically, oriented in the direction of the kilometre network of the Gauss-Krüger geographic coordinate system. The average measurement error was not defined.

Basic data on ground magnetic measurements

In all three cases (A – C), the vertical component of the intensity of the magnetic field Z was measured. In the Podunajská nížina Lowland, the density of the measurement was 1 point/km^2, in the Východoslovenská nížina Lowland 4-6 points/km^2. The density of the points in the Vienna Basin and the West Carpathian Flysch is not mentioned, but it is assumed to be 1 point/km^2. As reported by the authors of the reports, additional supplementary measurements (densifying) were performed in anomalous areas. The mean measurement error was within 3 nT.

In the case of Regions V and Z, magnetic induction of the total vector of the geomagnetic field of the Earth was measured in a step of 1 to 3 points/km^2. The mean measurement error was calculated to 1 nT.

3.3.1 Unified magnetic map of Slovakia

In 2001, work was completed on the project "Atlas of Geophysical Maps and Profiles" (Kubeš, 2001) and in 2008 "Magnetic Map of Slovakia" (Kubeš, 2008).

The objectives of these projects were:

- to compile a unified magnetic map of Slovakia at a scale of 1 : 500,000 and 1 : 200,000;
- to build a grid database of 125 x 125 m (the ability to build a magnetic map at a scale of 1 : 50,000) from the geomagnetic measurements and implement it into the GfIS (Geophysical Information System);
- to compile the maps of magnetic sources in the pre-Tertiary subsoil and the products of Tertiary and Quaternary volcanism with determination of their types, polarity and age for individual apparatuses, or bodies;
- to comprehensively evaluate and model more significant sources of magnetic anomalies;
- for selected magnetic anomalies to build a geological-geophysical source model, supplemented by a petrophysical characteristic;
- to summarize and evaluate the magnetic properties of rocks and rock complexes with regard to sounding measurements in selected wells (mainly reaching the pre-Tertiary basement).

To assemble a unified magnetic map of Slovakia aeromagnetic measurements with an average flight height of 80 m above the terrain relief were used. The results of ground measurements of the vertical component of the magnetic field obtained at the beginning of the 1960s in the Podunajská nížina and Východoslovenská nížina Lowlands and the western part of the Outer flysch zone were linked to these magnetically measured magnetic data. The Z-component magnetic field values were recalculated by magnetic field dip data (taken from Hurbanovo observatory) to total magnetic field induction T values. Supplementary geomagnetic measurements were performed between 2005 and 2008. T values were corrected on the normal field with International Geomagnetic Reference Field (IGRF – 1995, part of the Oasis montaj software). They were recalculated then on the altitude level of aviation measurements. Since the territory of Slovakia is located at the regional magnetic minimum, the calculated values of ΔT are in most cases in negative values. To get a picture of the course of the magnetic field (as we know it from older magnetic maps), all ΔT values were increased by +140 nT constant. This value was determined by statistical comparing the parameters of significant magnetic anomalies in old and newly created magnetic maps.

This way, a magnetometric database was obtained covering almost the entire territory of Slovakia in the form of grids in a regular network of 125 x 125 m, which corresponds to the requirements for creation of maps at scale 1 : 50,000 and a unified magnetic map of Slovakia was compiled (Kubeš, 2008; Fig. 3.1).

3.3.2 Geophysical information system (GfIS) – magnetometry

GfIS for magnetometry contains simultaneously 4 information levels:

1. Information level SK500,000, which includes:
   - coverage by GDB survey (magnetometric survey);
   - mag_125.GRD (ΔT grid field of the SR territory, 125 x 125 m);
   - mag_SK500,000.MAP (ΔT field map territory SR, M 1 : 500,000.
2. Information level JTSK200,000 – includes magnetometric data sorted by the 13 map sheets of the Basic Map of SR at scale 1 : 200,000:
   - Nr. Mag.GRD – Grid field ΔT (Map sheet number);
   - Nr. Mag.MAP – Map of ΔT field, scale 1 : 200,000.
3. Information level Regions – magnetometric data sorted by selected regions at scales of 1 : 50,000 to 1 : 200,000:
   - Region Mag.GRD – Grid field ΔT;
   - Region Mag.MAP – Map ΔT at a scale of 1 : 50,000 to 1 : 200,000.
4. Information level JTSK50,000 – magnetometric data sorted by 147 sheets of the basic map SR 1 : 50,000:
   - Map Mag.GRD – Grid field ΔT (Map number);
   - Map Mag.MAP – Map of ΔT field at a scale of 1: 50,000.

3.3.3 Magnetic map of Slovakia at scales 1 : 500,000 and 1 : 200,000

The Magnetic Map of the Slovak Republic ΔT was compiled from the magnetic data database at a scale of 1 : 500,000 (Figure 3. 1). The map provides a very varied magnetic picture of Slovakia, as the ΔT values range from -1,000 to +1,100 nT.

The most significant changes in ΔT values were found at sites of morphological elevations formed by products of mainly Tertiary and partly Quaternary volcanism.

In the Slovenské stredohorie Mts. there are mainly the volcanic mountain ranges of Pohronský Inovec, Štiavnické vrchy, Vtáčnik, Kremnické vrchy, Poľana, Javorie and Krupinská planina Plateau. In the Eastern Slovakia dominate the Neovolcanic Mountains of Slanské vrchy and Vihorlatské vrchy Mts.

The anomalous effects of Tertiary volcanism products were also found in the central part of the Pannonian Basin, Žiarska kotlina and Zvolenská kotlina basins.

The magnetic effects of neovolcanites in the wider area of Pohronská Polhora and north and NE of Rimavská Sobota are relatively distinct.

In the Východoslovenská nížina Lowland, the manifestations of neovolcanites were found especially in Malčice – Čičarovce – Kráľovský Chlmec – Streda nad Bodrogom – Zemplín – Brehov area.

In the area of the Cerová vrchovina Upland, the anomalous effects of Quaternary volcanism products are shown.

Tab. 3.1 Review of measurement campaigns

Region Nr.	Region name	A	Year	Transporter	Electronic navigation
1.	MALÉ KARPATY Mts. – SW	125	1981	Mi-8	-
2.	MALÉ KARPATY Mts. – NE	125	1980	Mi-8	-
3.	POVAŽSKÝ INOVEC Mts.	135	1979	Mi-8	-
4.	STRÁŽOVSKÁ HORNATINA HIGHLAND	135	1979	Mi-8	-
5.	MARTINSKÉ HOLE	135	1980	Mi-8	-
6.	M. FATRA AND ORAVSKÁ MAGURA Mts.	135	1980	Mi-8	-
7.	NW SLOVAKIA	140	1989	Mi-8, An-2	+
8.	TRIBEČ Mts.	135	1979	Mi-8	-
9.	VTÁČNIK AND POHRON. INOVEC Mts.	90	1976	Mi-8	-
10.	KREMNICKÉ VRCHY Mts.	90	1977	Mi-8	-
11.	ŠTIAVNICKÉ VRCHY Mts.	90	1976	Mi-8	-
12.	KRUPINSKÁ VRCHOVINA UPLAND	135	1979	Mi-8	-
13.	POĽANA AND JAVORIE Mts.	135	1977	Mi-8	-
14.	KRUPINSKÁ VRCHOVINA UPLAND – E	135	1978	Mi-8	-
15.	ĽUBIETOVÁ BELT	135	1978	Mi-8	-
16.	SLOVENSKÉ RUDOHORIE Mts. – W	135	1977	Mi-8	-
17.	LUČENSKÁ KOTLINA DEPRESSION	135	1977	Mi-8	-
18.	CEROVÁ VRCHOVINA UPLAND	100	1983	An-2	+
19.	RIMAVSKÁ KOTLINA DEPRESSION – W	135	1978	Mi-8	-
20.	MURÁNSKA PLANINA PLATEAU	0	1978	Mi-8	-
21.	LEVOČSKÉ VRCHY Mts.	35	1990	An-2	+
22.	SLOVENSKÉ RUDOHORIE Mts. – E	0	1977	Mi-8	-
23.	RIMAVSKÁ KOTLINA DEPRESSION – E	30	1983	An-2	+
24.	BRANISKO – ČIERNA HORA Mts.	35	1980	Mi-8	-
25.	KOŠICKÁ KOTLINA DEPRESSION – S	80	1983	An-2	+
26.	SLANSKÉ AND ZEMPLÍNSKE VRCHY Mts.	85	1980	Mi-8	-
27.	VIHORLATSKÉ VRCHY Mts.	20	1981	Mi-8	-
A	PODUNAJSKÁ NÍŽINA LOWLAND				
B	FLYSCH BELT WEST				
C	VÝCHODOSLOVENSKÁ NÍŽINA LOWLAND				
V	FLYSCH BELT EAST AND POLONINY Mts.		2006		
Z	SKORUŠINSKÉ AND CHOČSKÉ VRCHY, VEĽKÁ FATRA, VYSOKÉ AND NÍZKE TATRY, Mts. PODTATRANSKÁ KOTLINA DEPRESSION And KOZIE CHRBTY Mts.		2008		

A – azimuth of airborne profiles in [°]

The presence of Tertiary volcanism products has been proven in Podunajská nížina Lowland both by drilling and magnetic measurements. With the exception of the Burda Mountains, neovolcanic rocks are buried at relatively large depths and therefore their magnetic manifestation is relatively little pronounced.

The map also shows the anomalous effects of magnetic rocks in pre-Tertiary formations. The wider anomalies on the NW and W of Slovakia (the areas of Malacky – Skalica and Púchov – Bytča – Čadca – Námestovo) should be considered as manifestations of the profoundly deposited Proterozoic complexes of the North European platform that subduct below the Carpathian orogeny. We assume that the Obidowa-Słopnice unit with black complexes contributes to the overall image of the Earth's geomagnetic field.

The next anomalous territories were discovered in the wider area of Pezinok and the area of Galanta – Sereď – Hlohovec.

Relatively significant presence have magnetic rocks of the pre-Tertiary age in the territory Panické Dravce – Lučenec – Lovinobaňa – Málinec – Kokava nad Rimavicou – Klenovec – Muránska Dlhá Lúka – Rejdová – Dobšiná – Rudňany – Slovinky – Jaklovce – Vyšný Klátov – Seňa till the state border with Hungary.

The most significantly indicated are almost in-line magnetic structures:

a) Lovinobaňa – Málinec – Horná – Kerná;
b) Kokava nad Rimavicou – Klenovec – Hačava – Muránska Dlhá Lúka;
c) Panické Dravce – Lučenec – Breznička – Poltár – Hrachovo;
d) Dobšiná – Rudňany;
e) Košická Belá – Vyšný Klátov – Šaca.

A more extensive anomaly was found in the territory: Moldava nad Bodvou – Paňovce – Veľká Ida – Seňa – Buzica.

The Cerová vrchovina Upland is very distinct in the magnetic map.

Special attention has to be paid to the most extensive magnetic structure of Rimavská Sobota – Hnúšťa – Revúca – Slavošovce – Betliar – Krásnohorské Podhradie – Plešivec – Gemerská Ves – Uzovská Panica. Highest values of ΔT show the territory between Lubeník and Štítnik.

In Eastern Slovakia, anomalies in the vicinity of Zbudza appear to be very noticeable. A more extensive anomaly characterizes the territory on the Sečovce – Trhovište – Stretava axis. The presence of magnetically active rocks in Tertiary subsoil also reveals relatively large anomalies with relatively low amplitude in the Podunajská nížina Lowland.

A more detailed description of the nature of magnetic anomalies is presented in particular in the works of Kubeš (2001), Filo (2003), Bezák (2004) and Kubeš & Kucharič (2005).

In the Nízke Beskydy Mts. and the Poloniny Mts. a deficiency of magnetically active rocks is confirmed, possibly they are in great depths, which reduces (masks) their magnetic manifestation at the surface. Four major geomagnetic anomalies were found in the region. The most widespread negative anomaly is located in the area of the villages Ondavské Matiašovce – Žalobín – Jasenovce – Karná – Lieskovec. It reaches the amplitude -50 nT. Another vastly larger, more significant negative anomaly of the amplitude to -150 nT is located west of Nová Sedlica and north of the village of Zboj. By ground magnetic measurements, two positive anomalies were found in Stakčínska Roztoka and Ulič.

A different picture of the occurrence of magnetic rocks is given by geomagnetic measurements in the following areas: mountain ranges of Veľká Fatra, Starohorské vrchy, Chočské vrchy, Oravská vrchovina, Stredné Beskydy, Vysoké and Nízke Tatry, Spišská Magura, Skorušinské vrchy, Podtatranská kotlina Depression, Horehronské podolie, Kozie chrbty Mts. and Hornádska kotlina Depression. Altogether, more than 70 geomagnetic anomalies have been identified and described, which are caused by various petrographic types of rocks and rock complexes. These are in particular pyrrhotite, amphibolite, melaphyre, more basic granitoid differenciates – tonalites.

3. 4. Map of magnetic anomalies sources and their tectonic classification

The source map was progressively compiled region by region as they were gradually measured. Their names are based on the work by Mazúr & Lukniš (1980). This division was selected due to its use in the previous stage of 2001 (Atlas of Geophysical Maps and Profiles). The resource map does not include interpretations of insignificant, non-extensive anomalies that may be due to the morphology of the terrain, or civilization impact.

In terms of age we divided them into:

I: sources of magnetic anomalies in pre-Tertiary basement – Figure 3.3;

II: sources of magnetic anomalies of Tertiary and Quaternary volcanism – Figure 3.4.

I: Sources of magnetic anomalies in pre-Tertiary basement (Fig. 3.3)

The detected magnetic field anomalies have been interpreted in the past by various authors and various interpretive techniques that have been constantly evolving. Within

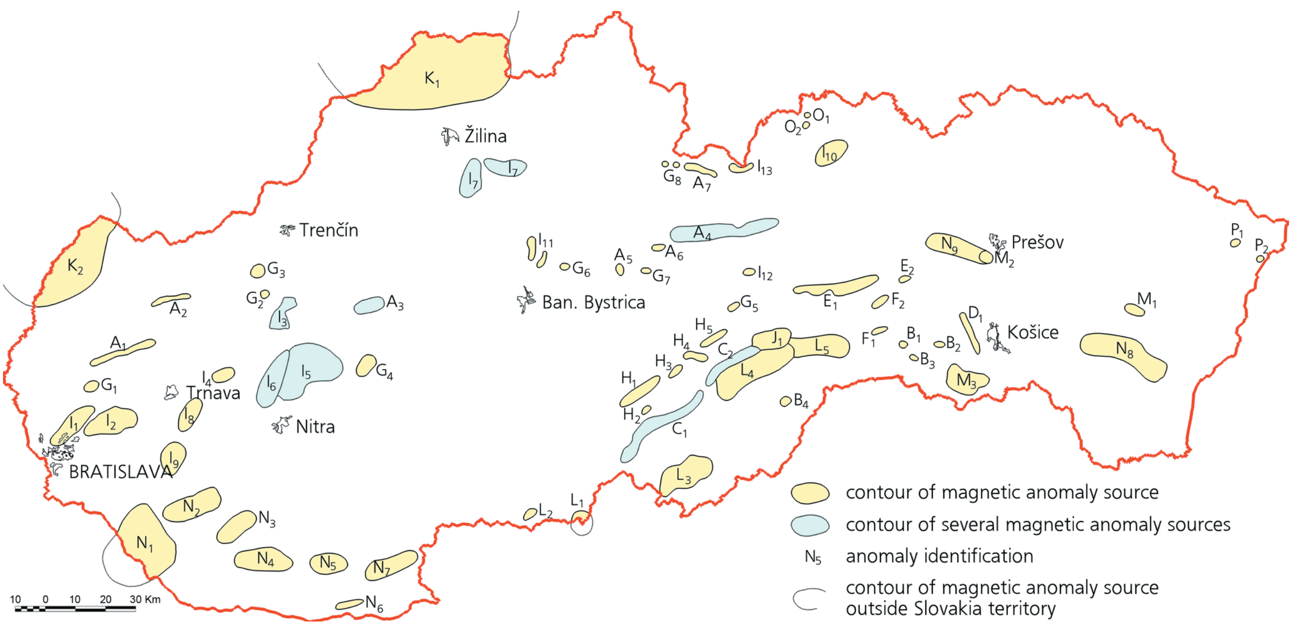

Fig. 3.3 *Sources of magnetic anomalies in pre-Tertiary basement*

the framework of the regional geomagnetic division of the SR, created on the basis of a magnetic map and regional geomorphological division by Mazúr & Lukniš (1980), extensive large-scale magnetic regions have been delineated, with contours of large anomalies, groups of anomalies of smaller size, and magnetic anomaly zones (Kubeš, 2001, 2008).

The more extensive anomalies are attributed to the anomalous effect of bodies of a geological origin. The group of anomalies forms the effects of bodies of smaller size dimensions of the same petrographic type on the limited territory of the given region (e.g. group of anomalies in the Tribeč mountain range). It is more complicated to interpret anomalous zones, where the effects of rocks of different petrographic type, age and tectonic relevance (e.g. anomalous zones in Slovenské rudohorie Mts.) are to be considered. In particular, discontinuity elements are particularly noticeable in the zones as a consequence of younger tectonic processes.

When classifying the anomalies into tectonic units, we make use of the basic tectonic division of the Western Carpathians (Biely, 1996). North of the Klippen zone is the Outer Western Carpathian belt, built mainly by flysch nappes thrust over the North European platform. South of it are the Inner Western Carpathians with the basic crust units of the Tatricum, Veporicum and Gemericum, which are built of a crystalline fundament and the Upper Palaeozoic-Mesozoic envelope.

From the point of view of the distribution of pre-Tertiary magnetic anomalies, they can be divided into three groups:

Magnetic anomalies falling into the area of the Outer Western Carpathians, the sources of which are found in the rocks of the platform below flysch nappes;

The anomalies in the Western Carpathian pre-Tertiary complexes (mainly in Proterozoic? – Palaeozoic, less in Mesozoic complexes), their sources crop out to the surface or are at different depths;

The anomalies in the Tertiary basins subsoil.

The area of the Outer Western Carpathians is characterized by the peaceful course of the magnetic field generated by the magnetic effects of the deep-sea resources of the North European platform. The opposite image provides the magnetic field of the Inner Western Carpathians due to different ferromagnetic minerals in the rocks and smaller depths and source dimensions.

Anomalous magnetic manifestations of varying intensity were recorded in almost all the basic crust units of the Western Carpathians, where they are located mainly in the rocks of the crystalline (in the Malé Karpaty, Považský Inovec, Tribeč, Malá Fatra and Slovenské rudohorie Mts.). Another major sources – albeit of lesser extent – are the basic volcanites of the Upper Palaeozoic and Mesozoic. Significant anomalies also occur in the Tertiary basins subsoil (Podunajská nížina Lowland, Ipeľská kotlina Basin, Lučenská kotlina Basin, Východoslovenská nížina Lowland).

The anomalous manifestations of magnetic rock substrates can be largely suppressed or obscured by the effects of surface and subsurface magnetic rocks induced by Tertiary and Quaternary volcanism products. Based on the results of the interpretation of individual anomalies or anomalous groups and the latest geological data, we have learned that the superposition of the anomalous effects of young volcanism and magnetically active rocks of Tertiary basement must be considered especially in the Podunajská nížina Lowland, the southern part of the Slovenské Rudohorie Mts., Lučenská and Rimavská kotlina basins and the SE part of the Východoslovenská rovina Plain. Also, when interpreting individual anomalies, it should be borne in mind that in many cases it is a superposition of the anomalous effects of rocks with different magnetisation, depth of deposition, geometry and orientation to the action of the current magnetic field of the Earth. The effects of several sources are most evident in the southern part of Slovakia (the area of Gemericum overthrust above Veporicum and the occurrence of the assumed fragments of Cadomian crystalline).

3.4.1 Magnetic properties of pre-Tertiary rocks

One of the pillars supporting the geological interpretation of the sources of magnetic anomalies in the Tertiary subsoil are the results of the study of the magnetic properties of the basic types of rocks. The volume magnetic susceptibility (KAPA) and, to a lesser extent, normal remanent magnetic polarization (NRMP) were determined in the physical laboratories of individual geophysical workplaces of the Czech and Slovak Republics. Measurements of susceptibility values were performed on nearly 10,000 samples taken from the outcrops, mine workings, structural and exploratory wells. To a lesser extent, the results of sounding magnetic measurements are also considered. It is logical that most of the data is available from regions where the Tertiary subsoil rocks crop out or are near the surface and are caught by mining or drilling. Many structural wells were located outside the centres of magnetic anomalies. Many wells often did not have the necessary depth and therefore did not capture the rocks of the subsoil, or terminated in its uppermost parts.

In the Outer Western Carpathians, the results of the study of the magnetic properties of the rocks show that the major source of large-scale anomalies are crystalline rocks in the subsoil of Tertiary complexes. According to the data, the magnitude of the magnetic susceptibility can be assigned to the crystalline rock 300 to 45,000 x 10^{-6} SI units. Increased values of magnetic parameters were found on samples of rocks of intermediate, basic to ultrabasic magmatism (granodiorites, diorites, gabbros, gabbrodiorites, gabbroamphibolites, peridotites and dunites). We note that in this wide range of susceptibility values, the largest proportion have the rocks with susceptibility to 1,000x10^{-6} SI units. Here we have to take into account the fact that only the highest parts of the crystalline structure, which are quite heavily weathered, are caught by the boreholes. Rocks with such magnetic parameters at such depths from the surface can not be the source of magnetic anomalies. Therefore, when interpreting the source, it is necessary to consider effective volume magnetic susceptibility in the range from 1.0 to 1,000 up to 35,000 x 10^{-6} SI units. Rocks in crystalline overburden with a value of up to 400 x 10^{-6} SI units in this case we consider to be practically non-magnetic.

In the Inner Western Carpathians, the Slovenské rudohorie and Slovenský kras Mts. are the most studied in petrophysics point of view. The systematic research of the magnetic properties of the rocks was carried out in the framework of the basic geological and geophysical research carried out within the framework of the research tasks of the former Dionýz Štúr Institute of Geology. The lowest data density on the magnetic properties of rocks in the Tertiary subsoil has the Podunajská nížina Lowland and the Východoslovenská rovina Plain. For example, there is a problem in the Podunajská nížina Lowland to explain the source of the Gabčíkovo anomaly and the Kolárovo gravity and magnetic anomaly. A similar problem also arises in interpreting the source of the Sečovce magnetic anomaly in the central part of the Východoslovenská rovina Plain.

A very interesting group of rocks of the Slovenské rudohorie and Slovenský kras Mts. are serpentinized ultrabasic rocks. They occur in the Young Palaeozoic and in the Mesozoic of Galmus and Slovenský kras Mts. These rocks exhibit magnetic susceptibility values ranging from 12,500 to 63,000 x 10^{-6} SI units; locally even cases with values up to 126,000 x 10^{-6} SI units have been defined. he direct dependence between the degree of serpentinization and the magnetic parameters has been proven. Non-metamorphosed ultra-base rocks (peridotites, dunites, pyroxenites) show significantly lower magnetic properties than the rocks with a relatively higher degree of serpentinization. The carrier of magnetic properties of rocks is a secondary magnetite, which is formed from olivine, pyroxene, amphibole or biotite. Sometimes, the oxidation environment where the serpentinite is formed also manifests itself with the presence of CO_2, which results in the formation of non-magnetic or weak magnetic magnesite. Further metamorphic alterations of serpentinites (steatitization, carbonization, chloritization, amphibolization) lead to a significant reduction of magnetic parameters to such an extent that the original high magnetic rock becomes practically non-magnetic. It has also been found that more serpentinized ultra-basic rocks have higher magnetic properties than less serpentinized ultrabasics.

Another significant source of magnetic anomalies are the products of diabase magmatism (diabases and their volcanoclastics). Their magnetic susceptibility ranges from 300 to 95,000 x 10^{-6} SI units. The sources of anomalies are also the larger bodies of amphibolites and hornblende diorites whose KAPA ranges from 300 to 11,000 x 10^{-6} SI units. We must also not forget the anomalous effects of melaphyres of the Choč unit with susceptibility values to 20,000 x 10^{-6} SI units.

An important information is also about the magnetic properties of metamorphic rocks – mica schists, gneisses, green and talc schists, and dark schists in particular. The susceptibility values observed for this type of rocks range from 350 to 5,700 x 10^{-6} SI units.

It should be noted that only about 25 % of the basic petrographic types of the Slovak part of the Western Carpathians are able to generate real magnetic anomalies of such intensity that they can be geologically interpretable. We also want to draw attention to the fact that the anomalous effect of magnetically active rocks depends not only on their magnetic parameters, but is mainly due to the depth of deposition, dimensions, morphology and the contrast of the environment in which the magnetic object is located.

3.5. Geological and tectonic classification of sources of magnetic anomalies in pre-Tertiary com- plexes

The basic characteristics of magnetic anomalies in the pre-Tertiary formations was elaborated within the framework of the Atlas of Geophysical Maps and Profiles – part Magnetometry (Kubeš, 2001), where the geophysical parameters of the anomalies are presented, as well as the geological characteristics of their sources. Anomalies were grouped according to geomorphological units. The interpretation of the geological source was based on the basic geophysical parameters of the anomaly, its size, depth and knowledge of the magnetic properties of the Western Carpathian rocks.

In this work we classify magnetic anomalies from the point of view of the relevance of their sources to the tectonic units of the Western Carpathians. The classification of the magnetic anomalies in the pre-Tertiary formations is given in Table 3.2.

Sources of anomalies are divided into groups according to tectonic relevance and according to lithology. The complexity of the tectonic structure of the Western Carpathians, as well as the often considerable depth of deposition of the sources of many anomalies, is a reason that the classification of some anomalies is not unambiguous and has a multi-variant solution. There are also cases where a magnetic anomaly is caused by a combination of effects from multiple sources.

According to the tectonic affiliation, the sources of magnetic anomalies in the pre-Tertiary formations of the Western Carpathians can be divided as follows (Fig. 3.3):

Sources of anomalies in the higher nappes of the Inner Western Carpathians:

A. basic volcanites of Hronicum;
B. basic to ultrabasic volcanites of Meliaticum;

Sources of anomalies in Palaeozoic fundament of Gemericum;

C. basic volcanites and phyllites of the Ochtiná tectonic unit
D. amphibolites of the Klátov tectonic unit;
E. basic metavolcanites of the Rakovec tectonic unit;
F. basic metavolcanites of the Gelnica tectonic unit.

Sources of anomalies in crystalline Tatricum and Veporicum:

G. amphibolites and metamorphites with positions of basic rocks;
H. mica schists and amphibolites of the lower Hercynian lithotectonic unit;
I. more basic differenciates of Hercynian granitoids
J. Rochovce granite .

Sources of anomalies in Cadomian fundament:

K. Cadomian fundament in the northern zone of the Western Carpathians (North-European platform, Brunia);
L. Cadomian (?) fundament in the southern zone and its overburden units.

Sources of anomalies of vague affiliation:

M. Ultrabasic rocks of unknown affiliation;
N. sources of anomalies of unknown membership at greater depths (probably mostly crystalline in combination with other sources);
O. Sources in the Inner Carpathian Paleogene;
P. Flysch Belt of the Outer Western Carpathians;

3.5.1 Tectonic affiliation of magnetic anomalies sources

A. Basic volcanites of Hronicum

The products of Permian basic and intermediate volcanism of the Ipoltica Group of Hronicum cause relatively significant magnetic anomalies in the Malé Karpaty Mts., in the southern part of the Strážovské vrchy Mts. and north-eastern part of the Kráľova hoľa part of the Nízke Tatry Mts. (Vozár, in Kubeš et al., 2001).

In the central part of the Malé Karpaty Mts., the anomalous effect on the surface of the cropping-out melaphyres in the Sološnica-Smolenice (A_1) area is clearly displayed. The linear zone of the ENE-WSW direction reaches a length of 20 km and a width of 1.4 to 2.2 km and is signalled by anomalies with an amplitude of up to 250 nT. This part of the zone includes covered bodies of melaphyres in the territory of Smolenice-Trstín.

Less pronounced is the effect of the assumed volcanites in NE parts of the mountain range (Brezovské Karpaty). The anomalous zone (A_2) passing through Brezová pod Bradlom reaches a length of up to 12 km and a width of 0.8 to 1.0 km. Anomaly values do not exceed 75 nT. We assume the upper edge of the rocks at a depth of about 100 to 150 m.

Melaphyre bodies are also associated with isolated magnetic anomalies with amplitude up to 75 nT in the wider neighbourhood of Nitrica (SW of Prievidza, Nitrické vrchy – A_3). Significantly different is the anomalous effect of basic and intermediate rocks in Malužiná – Nižná Boca – Liptovská Teplička – Hranovnica – Spišská Teplička (Malužiná – Vikartovce anomaly – A_4). Here the ground-based profile measurement revealed the presence of narrow magnetic zones of the linear type, which correlate very well with the course of geologically discovered occurrences of melaphyres of the Ipoltica Group. The anomalous zone of the E-W direction reaches a length of 40 km and a width of 3 to 5 km. The results of the measurements point to the fact that the volcanic rocks in this region have a larger area extent than documented in the past geological knowledge. The new measurements recorded the melaphyres in the Vysoké and Nízke Tatry Mts. (A_5, A_6 and A_7).

B. Basic to ultrabasic volcanites of Meliaticum

In the territory of the Slovenský kras Mts. the ground and aeromagnetic mapping has proven the presence of a large number of large-scale anomalies with a different amplitude (from 50 to 300 nT), which belong to the basics of the Meliaticum unit and the Bôrka nappe. An absolute lack of magnetic anomalies is characterized at the Plešivecká and Silická planina plateaus, where the Silicicum carbonates reach considerable thickness.

The Bôrka nappe borders the northern part of the Slovenský kras Mts. in the area between Jasov and Jelšava. Magnetic anomalies are generated by basics of this complex, which are scattered, have a small area extent, and indistinct amplitudes.

The sources of magnetic anomalies are serpentinites, which are found on the basis of tectonic slices, and are often embedded in complexes of Werfenian shales. They are predominantly metabasic rocks (metabasalts, green schists, glaucophanites (Mello, in Kubeš et al., 2001).

The variability in the petrographic composition of the rocks is similarly reflected in the variability of the magnetic properties of these rocks. Nearly all effusive rocks have undergone various alterations (serpentinization, spilitization, metamorphosis in the green and blue schists facies), which also affects their magnetic properties.

The melange-like character of Meliaticum is generally accepted and results in a similar magnitude of magnetic anomalies, such as those found in the Bôrka nappe, which are therefore of the local type, with a small area and reach negligible magnetic field values. According to their 2D modelling it is obvious that their rooting is shallow and rarely exceeds the level of 500 m below the surface.

The rock sources of magnetic anomalies in the Meliaticum are similar to those of the Bôrka nappe (Mello, in Kubeš et al., 2001). They are serpentines of the ophiolite formation of the Bodva valley, which can be found predominantly in the form of slices and protrusions pressed directly into the Werfenian Silicicum Fm., and the Jaklovce palaeobasalts (metabasalts), which are predominantly metamorphosed under anchizone conditions. The petrographic variability of volcanic and volcanoclastic rocks, which affects the magnetic properties, involves a different degree of metamorphosis in addition to the initial material, which is associated with the subduction – accretion process of the Meliaticum ocean closure.

In the magnetic maps, the effects of glaucophanites (B_1) and serpentinites (B_2, B_3, B_4) are most striking. The most significant are the Hačava (B_1), Jasov (B_2), Miglinec (B_3), anomalies in the area between Čoltovo and Bretka (B_4). The Hačava anomaly (B_1) represents the effect of a glaucophanite body oriented in the E-W direction. This is the largest surface occurrence of these rocks in the entire Western Carpathians. The Rudník-Jasov area (B_2) is characterized by two anomalies (Rudník and Jasov). The anomalies with amplitude 120, or 170 nT respond to serpentinite at the surface or they are covered by a thin layer of Tertiary sediments. The Miglinec anomaly (B_3) with amplitude of 125 nT is bound to a serpentine body in the valley of the same name. The anomalous zone reaches a length of up to 4 km and a width of about 1 km. The dimension of the anomaly thus far exceeds the surface dimension of the body. In the western part of the Meliaticum unit, the Bretka anomaly (B_4) is most noticeable. The anomalous zone of the ENE-WSW direction represents two partial anomalies – Čoltovo and Bretka. The anomaly at Čoltovo reaches an amplitude of up to 200 nT. It shows the anomalous effect of serpentinites, covered by Quaternary sediments at places. The Bretka anomaly with amplitude of about 300 nT is one of the most prominent in the region. The source of the anomaly is a large body of serpentinites, locally exposed, below the younger sediments. All basal and ultrabasic bodies, including glaucophanites, have relatively small thicknesses (up to 300 m).

*C. Basic volcanites and phyllites of the Ochtin*á *tectonic unit*

In the Ochtiná tectonic unit phyllites and schists dominate, often with a high carbon content, with less metacarbonates. Basic metavolcanites and ultrabasics are also present. In today's tectonic position, this unit crops out between the Veporicum and Gemericum. At the surface, it is exposed only in the narrow lane along the Ľubeník Line, but its occurrence is also assumed to be more southern in the Neogene subsoil and the rocks of the Gelnica Group.

The Ochtiná unit is relatively rich in the magnetic rocks. They are mainly diabase tuffs and tuffites, as well as phyllites probably with the addition of volcanoclastic material with increased magnetic parameters. Locally, the bodies of hornblende gabbros, gabbrodiorites, gabbro-amphibolites, and ultrabasics (serpentinites) are present. The anomalous zones of the southwest-northeast direction extend from Lučenec to the northeast direction – the Lučenec-Poltár (C_1) and Ľubeník (C_2) anomalies.

Magnetic maps show a more pronounced anomalous zone C_1. Here we assume a substantially larger area extent of the magnetic rocks and at the same time a greater complexity compared to the anomalous zone C_2. The anomaly reaches amplitude of 50 to 150 nT. The interpreted depth of the upper edge of magnetically active rocks ranges from 100 to 800 m below the surface with a patterned effective magnetic susceptibility around 12,000 x 10^{-6} SI units.

The Ochtiná tectonic unit may contribute, in combination with other sources, to the generation of other anomalies, e.g. the Gemer one (L_4).

D. Amphibolites of the Klátov tectonic unit

The typical sign of the monotone Klátov unit is the presence of metamorphosed rocks in the P-T conditions of the higher-temperature amphibolite facies. With the epizonally metamorphosed Rakovec Group it has a tectonic contact; the superincumbent of the Klátov Group is made up of discordantly deposited Westphalian and Permian rock complexes.

The Klátov unit is composed predominantly of amphibolites that are associated with gneisses, serpentinized spinel peridotites (metamorphosed to to antigorite serpentinites), and to a small amount with crystalline carbonates (Spišiak et al., 1985).

The zone of magnetic anomalies in the SE-NW direction, the source of which are the metabasics of the Klátov unit, is located W of Košice. It achieves amplitude of up to 250 nT with a length of 20 km and a width of up to 3 km (D_1). The most intense in the magnetic maps are the surroundings of Vyšný Klátov (Klátov anomaly).

Gnojek & Vozár (1992) were involved in interpreting the magnetic anomalies in the Klátov unit. They note that the amphibolite bodies in the north of the anomalous zone fall steeply to the WSW near the surface and at a depth of 1,500 m the slope angle drops to 40-30°. In the southern part of this band, the sources are tilted very steeply towards the WSW, up to the normal; however the reversible dip to ENE can not be excluded.

It is obvious that the major sources of anomalies are, in particular, amphibolites associated with biotite-hornblende gneisses that are characterized by effective magnetic susceptibility to 12,000 x 10^{-6} SI units. The anomalous bodies project to the surface or are located close to the surface and reach a considerable vertical dimension (Ivanička in Kubeš et al. 2001).

E. basic metavolcanites of the Rakovec tectonic unit

The Rakovec tectonical unit is one of the Gemericum Hercynian units. It is a volcanogenic-sedimentary formation characterized by basic volcanism with a tholeiite magmatic trend.

From the qualitative and quantitative interpretation of magnetic anomalies in the Rakovec Group by Filo and Kubeš (in Šefara, 1987) it has emerged that the main source of anomalies are mainly metabasic bodies at different depths. In Dobšiná-Nálepkovo area they are covered by a complex of metabasalt tuffs and tuffites.

Interpretation of Ivanička (in Kubeš et al., 2001) confirmed that the major sources of anomalies are metabasalt tuffs and tuffites with metabasalts positions. It is a very thick complex of basic rocks, whose magnetic properties are affected in particular by their mineral composition (amphibole, basic plagioclases, magnetite, ilmenite, hematite). Their interpreted effective magnetic susceptibility ranges from 12,000 do 20,000 x 10^{-6} SI units. The territory south of Spišská Nová Ves (Dobšiná – Hnilec – Nálepkovo) is accompanied by intensive magnetic anomalies with amplitudes up to 550 nT (E_1 – Rakovec). The anomalous zone reaches a length of 25 km and a width of up to 4 km. The continuous course of the anomalous zone is strongly disturbed in the vicinity of Hnilec, where the occurrences of bodies of Gemeride granites are proven. Another anomaly probably caused by the metabasalts of the Rakovec unit is located in the vicinity of Slovinky (E_2 – Slovinky) with amplitude of up to 50 nT. Their upper edge is interpreted to a depth of approximately 500 m below the surface with average magnetic susceptibility 12,000 x 10^{-6} SI units.

F. Basic metavolcanites of the Gelnica tectonic unit

The Gelnica unit builds a substantial part of the Palaeozoic of the Spišsko-gemerské rudohorie Mts. It is composed mainly of flysch sediments (sandstones and claystones) and synchronous rhyolite-dacite, rare basic volcanites.

In the eastern part of the Slovenské rudohorie (Volovské vrchy Mts.) there are numerous local anomalies

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with maximum amplitude of up to 75 nT and only exceptionally up to 100 to 150 nT. The previous interpretations were devoted mainly to Švedlár, Mníšek nad Hnilcom, Smolník, Pača and Henclová. Kucharič (1986) attributed the magnetic anomalies to the surface or near-surface variegated volcanic complex, represented mainly by bimodal diabase-keratophyre formation.

More intense anomalies are likely to show a larger accumulation of intermediary and basic volcanism products of the Bystrý Brook Fm. (Ivanička et al., 2001). In the magnetic maps, the effects of the above mentioned rocks in the Úhorná – Smolník – Smolnícka Huta (F_1 – Smolník anomaly) zone are most clearly visible. In a similar way, we characterize the Švedlár anomalous zone (F_2). In both cases, there are sources of magnetic anomalies on the surface, or close to the surface at depth max. up to 200 m.

In magnetic maps, the linear interface NE-SW with the axis Gelnica – Helcmanovce – Mníšek nad Hnilcom – Betliar is significantly displayed. This interface divides the Gelnica unit into two parts – the West and the East ones. The main difference between them rests in the fact that the western part is considerably richer in the occurrence of magnetic rocks at the surface or in the immediate vicinity of the surface.

G. Amphibolites and metamorphites with positions of basic rocks in crystalline of Tatricum and Veporicum units

Anomalous effects of sources of magnetic anomalies of this type were dealt with by Filo & Kubeš (in Šefara et al., 1987) mainly in the Malé Karpaty, Považský Inovec, Malá Fatra and Tribeč Mts.

In the Malé Karpaty Mts. the anomalous effect of the extensive body of amphibolites (Vozár in Kubeš et al., 2001) is manifested in the territory NW of Pezinok (G_1 – Pernek anomaly). The low values of the measured field here range from 25 to 50 nT and correlate very well with the morphology of the terrain. Relatively positive anomalies of morphological elevations and relatively negative anomalies of morphological depression are evidenced by the fact that amphibolite bodies reach only a relatively small thickness (up to 300 m). It cannot be excluded that the source of this anomaly may be somewhat more basic granitoid differenciates just below the surface.

Similarly to the Malé Karpaty Mts., the bodies of amphibolites in the eastern part of the Nízke Tatry Mts. are also displayed, where only terrestrial magnetic field measurements were performed.

In the Považský Inovec Mts. we are attributed to amphibolites the anomalies at Hrádok – G_2 and Kálnica – G_3 (Határ & Ivanička in Kubeš et al., 2001). The anomaly at Kálnica may be partly caused by volcanites of the Upper Palaeozoic. In both cases these are bodies with a greater depth range (over 1,000 m).

Amphibolite bodies with a relatively small thickness (less than 300 m) cause negligible magnetic anomalies in the eastern part of the Tribeč mountain range (G_4 – Skýcov), which represent three local anomalies with an amplitude of 50 to 150 nT. Maximum values are bound to more pronounced morphological depressions, controlled by the river network. The peaks of the magnetically active rocks appear the closest to the surface just in these sharp incised valleys. The source of local anomalies is the complex of mica schists with amphibolite positions.

In the Slovenské rudohorie Mts. there are anomalies in the territory of SW of Muránska Huta (G_5). This is part of a series of Muráň granite-gneisses, in which the amphibolites intercalations also appear. The entire complex of magnetic rocks does not exceed a thickness of 750 m. Amphibolites of this type are found in the Nízke Tatry Mts. near Bukovec (G_6) and Brezno (G_7) and in the Vysoké Tatry Mts. near Žiar (G_8).

H. Mica schists and am*phibolites of the lower Hercynian lithotectonic unit*

In the territory of Lovinobaňa – Málinec – Kokava nad Rimavicou – Klenovec – Rimavská Píla – kóta Tŕstie – altitudinal point Krížna Poľana (Brezina) – Muránska Dlhá Lúka, the existence of a complicated magnetic zone with amplitudes from 50 to 300 nT was verified by aeromagnetic and terrestrial magnetic measurements (Figure 3.3). The zone is oriented in the NE-SW direction and reaches a length of almost 50 km (anomalies H_1 až H_5 – Málinec, Rovné, Kokava, Klenovec and Píla).

This linear magnetic field, Filo (in Bodnár et al., 1988) attributed to the presence of mica schists complexes with the positions of amphibolites, also pointing to the presence of small bodies of serpentinites (the Uhorské vicinity). These magnetic mica schists are part of the lower Hercynian lithotectonic unit, which came to the surface within palaeoalpine tectonic processes of mainly transpressional character. Therefore, it creates a complicated structure, which is also reflected in the complexity of the magnetic zone. The magnetic properties of the mica schists are so pronounced that they also manifest themselves below the non-magnetic granitoid complexes of the Middle Hercynian lithotectonic unit up to 3 km deep. Conversely, the mica schists rocks, which we interpret as part of the middle lithotectonic unit, are mostly non-magnetic.

Our interpretation confirms that the main source of the anomaly are garnet-bearing mica schists with amphibolites (Bezák in Kubeš et al., 2001). In the southwest part of the zone, the effects of metasediments, metavolcanites and black shales of unknown classification are also shown. The results of the study of the magnetic properties of rocks from the KH-1 borehole show that the rock of this complex is greatly enriched in pyrrhotite, which affects the magnetic parameters, especially the values of natural remanent magnetic polarization.

The minimum proportion has the mica schist complex in the vicinity of Kokava nad Rimavicou (Kokava anomaly – H_3). Interesting is the position of the Klenovec anomaly (H_4). The source of the anomaly are again mica schist rocks with a clear orientation in the E-W direction. The whole complex goes submerges to S to a depth of about 1,000–1,500 m below a non-magnetic or very weak magnetic complex formed by albitized biotite paragneisses. Larger area extent have mica schist rocks in the area of Rimavská Píla – Muránska Dlhá Lúka (H_5). However, the thickness of the complex is considerably smaller than in the case of the Málinec (H_1) or the Klenovec (H_4) anomaly.

I. More basic differenciates of Hercynian granitoids

The results of the study of the magnetic properties of granitoids showed two important facts. The first is that the main carriers of magnetic parameters are mainly magnetite and titanomagnetite. The other is that the magnetic properties of the rocks are directly dependent on the degree of basicity of the rocks. In the case of granitoids, it is an increase in magnetic parameters (mainly magnetic susceptibility) in the order: biotite granodiorite – tonalite – hornblende diorite – gabbrodiorite. An exception is the Rochovce granite with a high content of magnetite, which belongs, however, to another age group.

The results of the geophysical and geological interpretation of the magnetic anomalies that we give to the granitoids bodies in the Tatricum and Veporicum crystallines have brought further insights. We start from the fact that the amplitude of the ΔT anomaly varies from 40 to 100 nT. The highest anomaly amplitudes have been found in regions where the magnetic rocks of granitoids rise directly to the surface or are located at depths of up to 500 m below the surface. Here we list the occurrences of granitoids in the north-eastern part of the Považský Inovec Mts., in the southern part of Strážovské vrchy Mts., in Malá Fatra Mts. and in the central part of the Tribeč mountain range. They are predominantly smaller-dimensional bodies of relatively small thickness.

The amplitude of the anomalies changes very little with regard to the depths of the sources and their thickness. This would indicate that the deeper the source is, the higher magnetic parameters and the higher basicity it has. It is possible to document the results of the geological and geophysical interpretation of magnetic anomalies from the southwest part of the Malé Karpaty Mts., the southern part of Považský Inovec Mts., the Embayment of Topoľčany (the Višňovce Depression), but mainly from the central part of the Podunajská nížina Lowland.

In the Malé Karpaty Mts. dominates Svätý Jur magnetic anomaly (I_1), which accompanies almost the entire NE part of the Bratislava Massif. Kohút (in Kubeš et al., 2001) considers granitoid complex (granodiorite-diorite) with a top edge at a depth of up to 2.0 km, found in the base of the practically non-magnetic Bratislava granitoid. We also consider the presence of basic granitoids in case of Grob anomaly (I_2). They are located at a depth of 2.5 to 3.0 km. The mutual spatial position of the sources of the anomalies I_1 and I_2 is influenced by the Malé Karpaty fault system of NE-SW direction, along which not only the source of the Grob anomaly has submerged towards SE, but also its shift towards NE. We cannot exclude the other interpretation of these anomalies, which is based on the views of the overthrust tectonic structure of the Malé Karpaty Mts., which admits magnetic complexes of metamorphites in the basement of non-magnetic granitoids of the Bratislava Massif.

Mountain range of Považský Inovec is rich in the occurrences of more basic differenciates of Tatricum granitoids (Határ in Kubeš et al., 2001). The discussed rocks form a complicated but apparent anomalous zone of the NE-SW direction with a length of about 70 km and a width of 5 to 7 km. It includes not only magnetic Inovec (I_3) and Hlohovec (I_4) anomalies, but also Sereď (I_8) and Galanta (I_9) anomalies in the Podunajská nížina Lowland. The top edge of magnetically active rocks in the northern part of the mountain range is located at the surface or near the surface, but in the SW direction their depths reach a level of about 3.0 km below the surface (e.g. anomaly I_9).

In the magnetic map, the effects of more basic granitoid differenciates are quite evident especially in the SW parts of the Tribeč mountain range, the Embayment of Topoľčany and Rišňovce depression. Surface and near-surface sources represent a group of anomalies in the wider area of Veľký Tribeč Hill (Tribeč – I_5; Ivanička in Kubeš et al., 2001).

Deeper deposited rocks are located in the territory of Topoľčany – Chrabrany – Ludanice (I_6 – Preseľany). The upper edge of the bodies is interpreted by Ivanička (in Kubeš et al., 2001) in a depth range of 1.0 to 1.5 km. The most extensive anomaly with amplitude of 75 nT was found in the area of Šurianka – Preseľany – Lefantovce – Čajkovce. The anomaly centre is located in the immediate vicinity of Preseľany, where the top edge of the source should be 1.7 to 2.0 km deep. In the southwest, the upper edge of the rocks submerges to a depth of more than 2.5 km.

In the area of Malá Fatra Mts. we define two anomalous areas where the effects of granitoids are shown. At places, they are accompanied by small positions of the amphibolite bodies at the near-surface level. The anomalous area is located in Kriváň as well as in Lúka parts of Malá Fatra Mts. (Malá Fatra anomalies – I_7; Kohút in Kubeš et al., 2001).

Kežmarok magnetic anomaly (I_{10}) forms a large-scale structure in the space Levoča – Torysky – Podolínec – Lendak – Kežmarok – Levoča, which almost coincides with the central part of the Levočské vrchy Mountains. Its amplitude with a maximum in the area of Bušovce does not exceed 20 nT, but is very readable. The first interpretation was performed by Gnojek et al. (1992), which set the upper magnetic edge at a depth of 4 km with effective magnetic susceptibility 10,000 x 10^{-6} SI units. After quantitative interpretation and modelling along the seismic profile no. 750/92 and correction with the data from reflex seismics (Hrušecký in Kubeš et al., 2001), a body model with a ceiling at a depth of about 2,500 m below the surface, with an average thickness of about 1,000 m, was accepted. It is assumed that such a large-scale magnetic anomaly is generated by more basic differenciates of Tatricum crystalline granitoids. However, based on the results of the interpretation and modelling of the magnetic anomaly after the seismic profile, it turns out that the magnetic mass continues further north through the Klippen band, suggesting that it is a combination of multiple sources with the influence of the platform. The magnetic effect of tonalites can be observed in the Nízke Tatry Mts. near Slovenská Ľupča (I_{11}), and Vernár (I_{12}) and Tatranská Štrba (I_{13}).

J. Rochovce granite

In the middle part of the Slovenské rudohorie Mts., a significant anomaly (J_1 – Rochovce) of 350 nT, induced by the Cretaceous Rochovce granite with a high concentration of magnetite was found by magnetic measurements.

One of the first interpretations of the Rochovce magnetic anomaly was carried out by Filo already in 1977. He assumed that the anomaly produce ultrabasic rocks at a depth of 1,200 m. KV-3 structure borehole in the depth range 0 to 550 m captured phyllites belonging to the Southern Veporicum, the 50 m thick position of the more acidic granitoids (aplites) and the 100 m thick position of the metabasites. In the interval of 700 to 1,600 m the presence of granites was found. Because of its magnetic properties, this granite has an exceptional position in the area of the Western Carpathians.

The results of the geochemical survey also proved the presence of W-Mo mineralization in the southern part of the abnormal anomaly (Václav et al., 1990). For this reason, a large number of RO-1 to RO-22 drilling wells was implemented here. It was proved by the drills that the relief of the upper edge of the Rochovce granite ranges from 500 to 725 m below the current surface.

In the Southern Veporicum there are also rare magnetic anomalies, which may be leucocrate granitoids of Permian or Alpine age, probably also with increased concentrations of magnetite.

K. Cadomian fundament in the northern zone of the Western Carpathians (North-European Platform, Brunia)

The territory of the Západné Beskydy Mountains, the Stredné Beskydy Mountains and the Záhorská nížina Lowland are accompanied by significant regional magnetic anomalies (K_1 – Beskydy, K_2 – Skalica) whose centre is located outside the Slovak Republic. Their amplitude in our territory reaches up to 120 nT. In the Západné and Stredné Beskydy Mts., the anomaly is oriented in the E-W direction, about 50 km in length. In the Záhorská nížina Lowland it reaches up to 40 km in the direction of NE-SW.

The issue of geological interpretation of sources of anomalies in the flysch rock basement have recently been given considerable attention by a wide range of geologists and geophysicists. The origin of magnetic anomalies of this regional type is not yet clearly explained. One group of authors is based on a classical interpretation in the sense that the anomaly is caused by one or several genetically related sources found in the crystalline of the platform. The second group is based on data on the magnetic susceptibility of rocks that suggest that crystalline surface forms a significant interface that can explain its relief based on the interpretation of magnetic field anomalies. Based on our results of interpretation of the Beskydy and Skalica anomalies, we find that when determining the depth of the sources of magnetic anomalies one should consider both alternatives. In general, the complexes of the intermediate, basic, exceptionally also ultrabasic rocks as well as the metamorphites of the basic rocks are considered to be the decisive source of magnetic anomalies. Crystalline is represented in this territory by Cadomian units of Brunia and it contains just such types of rocks, which are also exposed at the surface.

According to the results of the Jablunkov 1 structural borehole located at the peak of the Beskydy anomaly, the Palaeozoic envelope of the platform and the upper part of the crystalline have low magnetic parameters and their influence on the overall character of the Beskydy anomaly is negligible. Interpreted anomaly (K_1) is caused by rocks inside the crystalline. The decisive influence on the anomalous field of the region have rocks with an upper margin in the depth range of about 6.0 km in the border area of the Czech Republic, Poland and Slovakia, which are submerging down to the depths of 10 to 12 km southwards (Bytča surroundings). It is possible that this rock complex continues to the south, as interpreted by Filo on the 2T profile.

A similar geophysical-geological interpretation was obtained also in the analysis of the source of the rock anomaly (K_2). Here we want to note that the Skalica anomaly continues on the territory of the Czech Republic, where the magnetic rocks of crystalline form its relief. Proof of this is the difference in the maximum values of the anomaly. We have already mentioned that in the case of the Beskydy anomaly, magnetic field values were measured to 120 nT, in the vicinity of Břeclav amplitudes reach 260 to 400 nT. Such differences in the anomaly amplitude are not related to the depth of source, but mainly to the lithological composition and the magnetic properties. We believe that magnetic rocks in the south-eastern part of Moravia are predominantly gabbro – gabbrodiorite – gabbronorite and gabbroamphibolite rocks.

L. Cadomian (?) fundament in the southern zone and its superincumbent units

In the southern part of the Inner Western Carpathians, there are several magnetic anomalies in the Tertiary basement, which we cannot be explained by the effects of well-known units (mainly the mica schists of the Southern Veporicum and the Ochtiná unit). Based on the interpretation of the tectonic structure of the Tertiary basement in the southern part of Slovakia, in addition the crystalline rocks exposed in the Western Carpathians, the occurrence of fragments of the Cadomian fundament is likely (Bezák et al., 1997). This interpretation is also supported by the xenoliths of the unknown crystalline of the basalt magma in the Fiľakovo region and the presence of heavier substances in the Tertiary basement in this region with similar densities as the Cadomian crystalline in the North European platform.

In the Ipeľská kotlina Basin, the dominant position has the Kováčovce magnetic anomaly (L_1) with amplitude of up to 300 nT. It is part of the magnetic zone of the ENE-WSW direction, which continues from the territory of Hungary. At the centre of the anomaly was the structural well MV-12 with a final depth of 1,102 m. In the depth range 0–558 m, non-magnetic Tertiary sediments are present. In the range of 558–900 m, the position of garnet-bearing mica schists, which exhibit relatively high magnetic susceptibility (6,300 x 10^{-6} SI units) and NRMP (around 1000 nT), was verified. The lower part of the borehole (interval 900–1,102 m) consists of amphibolite gneisses and amphibolites with an average susceptibility of 4,100 x 10^{-6} SI units and NRMP 7500 nT. Filo (in Vass, 1979), interpreted the Kováčovce magnetic anomaly as the effect of the amphibolite body, enriched in the magnetite at places. Based on the findings from the MV-12 drill, we assume that the magnetic anomaly is probably caused by the combined effect of the magnetic mica schists of the Southern Veporicum and the underlying probably Cadomian fundament with the content of the metabasic rocks.

In the territory of Trebušovce – Lesenice (L_2 – Lesenice anomaly, Figure 3.3) magnetic anomaly ΔZ with amplitude up to 50 nT and ΔT with amplitude up to 25 nT was detected. The top edge of the magnetic body is interpreted at a depth of about 500 m below the current surface. The geological source of the anomaly is vague. It is probably part of the relics of the Ochtiná unit rocks similarly to the territory NW of Lučenec. Magnetic parameters and orientation of an anomaly in the NE-SW direction would indicate this. However, the anomalous effect of the mica schists of the Southern Veporicum and the Cadomian fundament cannot be excluded.

There are two positive, extensive large-scale magnetic anomalies of regional character in the Cerová vrchovina Upland, with amplitudes up to 300 nT, which have been merged due to the proximity of their sources to one anomaly (L_3 – Blhovce-Fiľakovo). The Blhovce-Fiľakovo magnetic anomaly was the subject of an interpretation in the construction of a structural-tectonic map of the Inner Western Carpathians. Filo & Kubeš (in Šefara 1987), both anomalies were considered to be part of a significant magnetic zone, which continues from the Blhovce area to the WSW up to the Börszönyi mountain range. The interpreted depth of the upper edge of the magnetic bodies was set within the range of 1.0-1.4 km. The lower boundary of the magnetic complex was estimated at 5.0-6.0 km. Based on the petrographic characteristics of the FV-1 borehole, which was located at the centre of the anomaly, it was assumed that the source of the anomaly are the Palaeozoic metabasics and the metasediments of Gemericum or Veporicum. The latest interpretation (Vozár in Kubeš et al., 2001) confirmed earlier interpretations. According to this, the magnetic effects originate from the Palaeozoic rocks, which are located in the Tertiary basement at a depth of more than 1,000 m below the surface. In our opinion, the metamorphic rocks in the borehole are affiliated to the Ochtiná unit and the mica schists of the Southern Veporicum, which probably overlie the assumed Cadomian fundament.

Another regional anomaly (Gemer L_4) is situated SE of Rožňava, in the territory of Gemerské Teplice – Licince – Gemerská Ves – Veľký Blh – Hrušovo – Ratková – Rákoš – Turčok. It occupies an area of about 300 km^2 and is oriented in the SW-NE direction. The upper edge of the magnetic rocks complex is interpreted at 4–4.5 km below the surface. Given the dimensions of the anomaly and magnetic and gravity parameters, it is likely that, similarly to the L_3 anomaly, it is induced, in addition to the magnetic rocks of the Ochtiná unit, by the presence of mica schists of the lower Hercynian unit and the fragments of the southern Cadomian fundament.

The Rožňava anomaly (L_5) is located in the wider area of Rožňava, in the area of Revúcka Lehota – Slavošovce – Roštár – Betliar – Drnava – Silica – Slanec – Gemerský Sad – Gemerské Teplice – Ľubeník and occupies an area of about 500 km^2. It is oriented in the E-W direction. The larger masses of basic metavolcanites and metavolcanoclastics belonging to the Rakovec Group (Vozár in Kubeš et al., 2001) were considered to be the source of the anomaly. Parts of the complex are smaller magma bodies of gabbrodiorites (Vozárová & Vozár in Rakús and Vozár, 1993). The upper edge of the magnetic complex is interpreted at a depth of about 3 km (west of the Štítnik fault) up to 4 km (east of the Štítnik fault). Given these and other physical parameters of the anomaly, it is very likely that the influence of the crystalline of the predicted underlying Cadomian fundament contributes to the source of the anomaly.

Ultrabasic rocks of vague affiliation

The Zbudza magnetic anomaly (M_1) is located in the northern part of the Východoslovenská nížina Lowland. It has northwest – southeast direction and max. amplitude of 80 nT. By quantitative interpretation and modelling, the basic parameters of the magnetic body, the upper edge of which lies at a depth of about 2.6 km with a thickness of 800 to 1,000 m, were determined. The upper edge of the body falls to the NNW (below the village of Zbudza) up to a depth of 3.6 km below the surface and at the SSE below Humenné to the same depth. Based on the results of the Zbudza-1 borehole, we assume, like Gnojek (1987a), that the sources of this anomaly are the serpentinized pyroxenites of unknown affiliation with a thickness of 1 km with an interpreted magnetic susceptibility 60,000 x 10^{-6} SI units.

The Bzenov anomaly (M_2) with amplitude up to 60 nT is oriented in the E-W direction. The main source of the Bzenov anomaly are most likely ultrabasic rocks below Branisko with a top edge at a depth of about 800 m below the surface. A body with a thickness of about 600 m is dippimg to the north.

Gnojek (1987b) gives an interpretation of the Bzenov magnetic anomaly in two variants. The first assumed in the Inner Carpathian Palaeogene basement the existence of rocks that correspond to the rocks in the crystalline regions, the second one magnetic rocks with a magnetic susceptibility of 20,000 x 10^{-6} SI units, which often occurs in gabbro and peridotite.

SW of Košice, on a relatively large area, magnetic anomalies of different amplitude and orientation have been verified. The entire anomalous region is known as the Komárovce magnetic anomaly (M_3). The Komárovce magnetic anomaly with amplitude of up to 300 nT is most visible in the areas of Paňovce – Čečejovce and Šaca – Veľká Ida – Komárovce. Less pronounced and less extensive anomalies were found in the area between Jasovo and Nováčany and east of Paňovce. The negative anomalies accompany the band of positive anomalies in their northern and north-eastern parts. It is an anomalous effect of the lower edge of magnetic rocks, inclined to the south, or to SW. The main sources of magnetic anomalies are probably serpentinized ultrabasic rocks captured by the KO-1 (Komárovce) borehole at a depth of 943.0 m, which according to some interpretations could belong to the Meliaticum. Their bottom edge was not verified with a 1,534 m final depth of the borehole. Elevated values of magnetic rocks have been found in rocks samples mainly in the depth range above 1,000 m. Magnetic susceptibility values move within the range 1,500–21,000 x 10^{-6} SI units.

The question of the interpretation of the source of magnetic anomalies in the wider area of Komárovce was also dealt with by other authors (Gnojek, Hovorka & Pospíšil, 1991, Gnojek & Vozár, 1992). In their interpretation of the source of the anomalies there are quite significant differences. In particular, there are differences in the data about the magnetic parameters of the object and especially the thickness of the source. In the first work, the authors assume a source thickness of up to 3,000 m and an effective volume magnetic susceptibility of 15,000 x 10^{-6} SI units, in the second work the lower edge of magnetically active rocks is laid down to a depth of 7 km, considering effective volume susceptibility up to 35,000 x 10^{-6} SI units. Based on our findings, we believe that the interpretation of the first authors (Gnojek et al., 1991) is much more realistic.

N. Magnetic anomalies sources of vague affiliation at greater depths

(probably mostly crystalline in combination with other sources)

The most comprehensible are the sources of magnetic anomalies buried at greater depths. These are sources in the Neogene basement of the Podunajská nížina Lowland (N_1 – N_7) and the Východoslovenská nížina Lowland (N_8). A special case is the N_9 anomaly in the Inner Carpathian Palaeogene. The sources of deep anomalies in the area of southern Slovakia can be of three kinds: they can be induced by the Tatricum and Veporicum crystalline rocks (basics, more granitoid differenciates, mica schists), whereas the influence of the fragments of the southern Cadomian fundament can also contribute, and the third source are the ultrabasic rocks, which intruded the crust in particular in the Tertiary and were associated with local asthenoliths ascent.

Several anomalies, the sources of which are probably metabasites in crystalline, are found in the Neogene basement in the Podunajská nížina Lowland. The most notable is the Gabčíkovo anomaly (N_1) with amplitude up to 200 nT. It also continues to the territory of Hungary. At the centre of the anomaly we interpret the presence of andesites with a top edge at a depth of about 3.2 km. In the western part and southeast of Gabčíkovo Hrušecký & Konečný (in Kubeš et al., 2001) suggest the presence of magnetic rocks of Tatricum crystalline with the top edge at a depth of about 5.0 km to 6.0 km. In the vicinity of the Gabčíkovo anomaly, drillings FGC-1, DS-1, DS-2, FGGA-1, FGHP-1, VTP-11, GPB-1 and CR-1 were realized with a maximum depth of up to 3,000 m. Neither of these drills has provided evidence of the presence of magnetic rocks in the Tertiary fill and no borehole reached the Tertiary basement. Based on the tectonic situation and the depth of the anomaly we assume its sources in the Tatricum crystalline or Cadomian fundamentals. Metabasic rocks are most likely to occur, as heavier masses are also indicated in this area.

Two significant magnetic anomalies – the Kráľov Brod (N_2) and Vlčany (N_3) – have been found in the Podunajská nížina Lowland, which are probably caused by more basic granitoid differenciates with amplitudes of 100 to 140 nT. The source of the Vlčany anomaly was interpreted to a depth of 5.0 to 6.0 km and to the Kráľov Brod 4.5 to 5.0 km below the current surface.

From the point of view of the deep burial of the source of the magnetic anomaly of Búč (N_6), there is an exception in the area of the Podunajská nížina Lowland. It is the only one that is shallowly deposited and is probably caused by basal to ultrabasic rocks in the underlying Mesozoic complex, which probably no longer belongs to the Western Carpathian units, but it is a Pelsonia block. We interpret its source at a depth of 0.6 km below the surface. In all three cases, the influence of the underlying Cadomian fundament can also be assumed.

The Bíňa anomaly (N_7) with a maximum amplitude of up to 75 nT in the eastern part of the Podunajská nížina Lowland is probably induced by the rocks of the mica schist complex (Hrušecký in Kubeš et al., 2001). It is located at a depth of 3.0 to 3.5 km. These rocks underlie the non-magnetic sediments without a volcanic fraction. The magnetic anomaly is oriented in the NE-SW direction. The interpreted source length is about 17 km and a width of about 7 km. Even in this case, we cannot exclude the influence of the underlying Cadomian fundament.

In the vicinity of Kolárovo in the Podunajská nížina Lowland there is a faint but extensive magnetic anomaly, coinciding with an intense positive gravity anomaly known from the geological literature as the Kolárovo anomaly (N_4). For the first time, this magnetic anomaly was observed in the "Structure-Tectonic Map of the Inner Western Carpathians" (Filo in Šefara et al., 1987). For the source of this anomaly the authors suggested basic rocks (gabbros and metabasics, gabbroamphibolites, gabbrodiorites) with effective magnetic susceptibility of 12,000 x 10^{-6} SI units, which should be located at a depth of 5 km with a thickness of about 7 km. At present, we give the Kolárovo anomaly in connection with the massive body of gabbroamphibolites (gabbrodiorites) with a top edge at a depth of 5.5–6.0 km. According to the interpretation, Bezák et al (1997) refers to crystalline rocks or the residue of the basics of the Meliaticum unit in the suture zone, which was also used for the output of partial asthenolith bodies in the Tertiary extension processes.

Rather ambiguous is the interpretation of the sources of a less pronounced, but extensive Strekov anomaly (N_5) with a depth of about 3.5–4.0 km. We assume that the sources of the anomaly are the same rock complexes, as in the case of the Kolárovo anomaly.

In the Východoslovenská nížina Lowland, the dominating position has the Sečovce anomaly (N_8) with amplitude to 100 nT. Man (1961), Pospíšil & Filo (1977), Mořkovský & Cverčko (1987) and Gnojek (1987a) were involved in the interpretation. They put the source depth in the range from 5.5 to 6.5 km with various effective magnetic susceptibilities (5,000–100,000 x 10^{-6} SI units). For its source, Janočko (in Kubeš et al., 2001) considers the complex of magnetic rocks at the southwest edge of the Pozdišovce-Iňačovce unit. They are bound to tectonic contact with the practically non-magnetic rocks of the Zemplín unit.

According to the present geological knowledge, the Pozdišovce-Iňačovce unit consists of phyllites of different compositions. We believe that this rock complex cannot be the source of an interpreted regional Sečovce anomaly. Structural boreholes made so far did not reach the Tertiary basement. According to our interpretations, the sources of the Sečovce anomaly are probably metamorphites of basic rocks with a roof at a depth of about 6.0 to 8.0 km. According to the interpretation of Bezák et al. (1997) the proximity of ascended asthenolith in the bedrock also contributes to the magnetic effect. Similarly, these types of anomalies are interpreted by Vass et al. (1988).

In the southern part of Šarišská vrchovina Upland, a relatively large area anomaly with amplitude of up to 40 nT (Šariš – N_9) was recorded by aeromagnetic mapping. It is oriented in the ESE-WNW direction, reaching a length of nearly 20 km and a width of about 6 km. Its eastern boundary is questionable due to lack of magnetic information for technical reasons. The top edge of this source is interpreted to a depth of 1.8–2.5 km. The Šariš anomaly is divided into two parts – the northern and the southern ones, based on the magnetic field. The northern part of the anomaly is caused by magnetic rocks whose upper edge lies at a depth of about 2,500 m. The southern part forms an anomalous effect of rocks at a depth of about 1,800 m. The anomalies in both parts of the Šariš anomaly were considered to be either more basic differenciates of the granitoids of the Western Carpathian crystalline, but neither the influence of the basic rocks of the crystalline of the North European platform is excluded, as we predict also in the case of the Kežmarok anomaly (I_{10}).

O. Sources in the Inner Carpathian Palaeogene

New anomalies have been detected in new terrestrial magnetic mapping in the Spišská Magura Mts. region, most likely due to Menilite Mb. (O_1 and O_2), which are located at or near the surface at Lendak and Hanušovce.

P. Flysch Zone of the Outer Western Carpathians

These little significant magnetic anomalies are again caused by the Menilite Mb. found at the surface at Roztoka and Ulič in Bukovské vrchy Mts. (P_1 and P_2).

3.6. Geomagnetic research in neovolcanites of Slovakia

The most significant magnetic anomalies in Slovakia were recorded in the areas of neovolcanic mountain ranges. They are characterized in particular by the rapid alternation of positive and negative anomalies in the range from -1,100 to +1,000 nT.

In the Slovenské stredohorie Mts. there are mainly Pohronský Inovec and Štiavnické vrchy (1), Vtáčnik (2), Kremnické vrchy (3), Poľana (4), Javorie (5) and Krupinská planina Plateau (6). In the Eastern Slovakia dominate the neovolcanic mountains Slanské vrchy (7) and Vihorlatské vrchy (8). The anomalous effects of Tertiary volcanism products were also found in Žiarska kotlina Basin (13) (Figure 3.4)

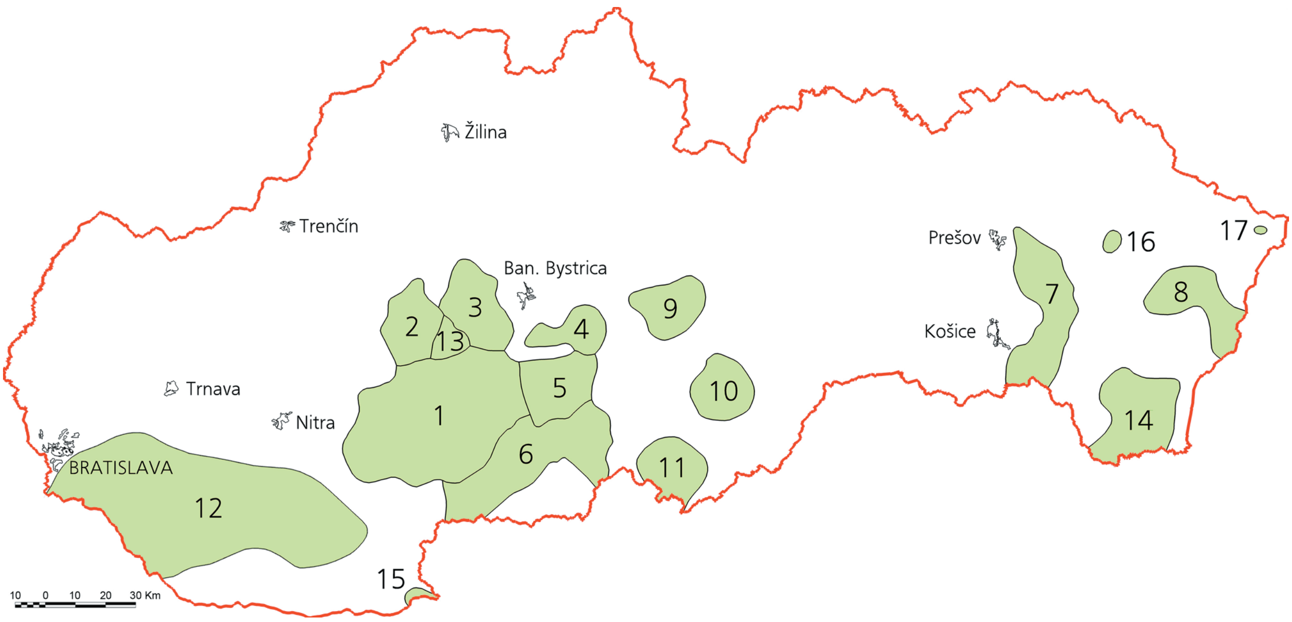

Fig. 3.4 *Distribution of neovolcanites in the territory of the Slovak Republic*
1: *Pohronský Inovec and Štiavnické vrchy Mts.;* **2:** *Vtáčnik Mts.;* **3:** *Kremnické vrchy Mts.;* **4:** *Poľana Mts.;* **5:** *Javorie Mts.;* **6:** *Krupinská planina Plateau;* **7:** *Slanské vrchy Mts.;* **8:** *Vihorlatské vrchy Mts.;* **9:** *wider vicinity of Pohronská Polhora;* **10:** *Pokoradzská tabuľa Plateau;* **11:** *Quaternary volcanism of Cerová vrchovina Upland;* **12:** *Podunajská nížina Lowland;* **13:** *Žiarska kotlina Basin;* **14:** *Východoslovenská nížina Lowland;* **15:** *Burda Mts.;* **16:** *buried volcanites at Humenné;* **17:** *buried volcanites at Zboj Village.*

Tab. 3.2 Tectonic classification of sources of magnetic anomalies in the pre-Tertiary formations of Slovakia

Sources of magnetic anomalies		Geographic region	Name of magnetic anomaly	Label in map	Source depth (km) below surface
A	Basic volcanites of Hronicum	Malé Karpaty Mts.	Sološnica-Smolenice	A_1	0–0.2
		Brezovské Karpaty Mts.	Brezová	A_2	0.1
		Strážovské vrchy Mts. – South	Nitrica	A_3	0–0.3
		Kráľova hoľa Nízke Tatry Mts. – North	Malužiná-Vikartovce	A_4	0
		Nízke Tatry Mts. – South	Malužiná-Vikartovce	A_5	0
		Nízke Tatry Mts. – South	Malužiná-Vikartovce	A_6	0
		Vysoké Tatry Mts.	Malužiná-Vikartovce	A_7	0
B	Basic to ultrabasic volcanites of Meliaticum	Slovenský Kras Mts. – East	Hačava	B_1	0–0.1
		Slovenský Kras Mts. – East	Jasov	B_2	0–0.1
		Slovenský Kras Mts. – East	Miglinec	B_3	0–0.3
		Slovenský Kras Mts. – West	Bretka	B_4	0–0.1
C	Basic volcanites and phyllites of the Ochtiná tectonic unit	Slovenské rudohorie Mts.	Lučenec-Poltár	C_1	0.1–0.8
		Slovenské rudohorie Mts. – centre	Ľubeník	C_2	0.1–0.5
D	Amphibolites of the Klátov tectonic unit	Slovenské rudohorie Mts. – East	Klátov	D_1	0–0.2
E	Basic metavolcanites the Rakovec tectonic unit	Slovenské rudohorie Mts. – East	Rakovec	E_1	0
		Slovenské rudohorie Mts. – East	Slovinky	E_2	0.5–0.7
F	Basic metavolcanites of the Gelnica tectonic unit	Slovenské rudohorie Mts. – East	Smolník	F_1	0–0.2
		Slovenské rudohorie Mts. – East	Švedlár	F_2	0–0.2
G	Amphibolites and metamorphites with positions of basic rocks in crystalline of Tatricum and Veporicum	Malé Karpaty Mts.	Pernek	G_1	0
		Považský Inovec Mts.	Hrádok	G_2	0.1–0.2
		Považský Inovec Mts.	Kálnica	G_3	0.1–0.2
		Tribeč Mts.	Skýcov	G_4	0–0.5
		Slovenské rudohorie Mts. –centre	Muráň	G_5	0.0–0.2
		Nízke Tatry Mts.	Bukovec	G_6	0
		Nízke Tatry Mts.	Brezno	G_7	0
		Vysoké Tatry Mts.	Žiar	G_8	0
H	Mica schists and amphibolites of Lower Hercynian lithotectonic unit	Slovenské rudohorie Mts.– West	Málinec	H_1	0.6–1.0
		Slovenské rudohorie Mts. – West	Rovné	H_2	0.1–0.5
		Slovenské rudohorie Mts. – West	Kokava	H_3	0.1–0.3
		Slovenské rudohorie Mts. – West	Klenovec	H_4	0.0–0.5
		Slovenské rudohorie Mts. – West	Píla	H_5	0.1–0.5
I	More basic differenciates of Hercynian granitoids	Malé Karpaty Mts.	Svätý Jur	I_1	2.0
		Podunajská nížina Lowland	Grob	I_2	2.0–2.5
		Považský Inovec Mts.	Inovec	I_3	0.5–0.7
		Považský Inovec Mts.	Hlohovec	I_4	0.1–1.5
		Tribeč Mts.	Tribeč	I_5	0–0.5
		Tribeč Mts.	Preseľany	I_6	1.0–2.0
		Malá Fatra Mts.	Malá Fatra	I_7	0–0.6
		Podunajská nížina Lowland	Sereď	I_8	3.0–3.5
		Podunajská nížina Lowland	Galanta	I_9	3.5
		Levočské vrchy Mts.	Kežmarok	I_{10}	2.5–3.0
		Nízke Tatry Mts.	Ľupča	I_{11}	0
		Nízke Tatry Mts.	Vernár	I_{12}	0
		Vysoké Tatry Mts.	Štrba	I_{13}	0
J	Rochovce granite	Slovenské rudohorie Mts. – centre	Rochovce	J_1	0.5–0.8

Tab. 3.2 – continuing

Sources of magnetic anomalies		**Geographic region**	**Name of magnetic anomaly**	**Label in map**	**Source depth (km) below surface**
K	Cadomian fundament in the northern zone	Západné and Stredné Beskydy Mts.	Beskydy	K_1	> 6.0
		Borská nížina Lowland	Skalica	K_2	> 6.0
L	Cadomian fundament in the southern zone and its overlying units	Ipeľská kotlina Basin	Kováčovce	L_1	1.0
		Ipeľská kotlina Basin	Lesenice	L_2	0.5
		Lučenecká kotlina Basin	Blhovce- Fiľakovo	L_3	1.0–1.5
		Slovenské rudohorie – East	Gemer	L_4	4.0–4.5
		Slovenské rudohorie – East	Rožňava	L_5	3.0–4.0
M	Ultrabasic rocks of vague affiliation	Východoslovenská rovina Flat	Zbudza	M_1	2.7
		Šarišská vrchovina Upland	Bzenov	M_2	0.8
		Košická kotlina – West	Komárovce	M_3	0.3–1.0
N	Sources of magnetic anomalies of vague affiliation	Podunajská nížina Lowland	Gabčíkovo	N_1	5.0–6.0
		Podunajská nížina Lowland	Kráľov Brod	N_2	4.5–5.0
		Podunajská nížina Lowland	Vlčany	N_3	5.0–6.0
		Podunajská nížina Lowland	Kolárovo	N_4	5.5–6.0
		Podunajská nížina Lowland	Strekov	N_5	3.5–4.0
		Podunajská nížina Lowland	Búč	N_6	0.6
		Podunajská nížina Lowland	Bíňa	N_7	3.5–4.0
		Východoslovenská rovina Flat	Sečovce	N_8	6.0–8.0
		Šarišská vrchovina Upland	Šariš	N_9	1.8–2.5
O	Sources in ICP	Spišská Magura Mts.	Hanušovce	O_1	0
		Spišská Magura Mts.	Lendak	O_2	0
P	Flysch Belt of the Outer Western Carpathians	Bukovské vrchy Mts.	Roztoka	P_1	
		Bukovské vrchy Mts.	Ulič	P_2	

Relatively significant are the magnetic effects of neovolcanites in the wider area of Pohronská Polhora (9), Pokoradzská tabuľa Plateau (10) and Východoslovenská nížina Lowland (14).

In the area of Cerová vrchovina Upland, the anomalous effects of Quaternary volcanism products (11) are clearly manifested (Fig. 3.4).

The presence of Tertiary volcanism products has been proven both by drillings and magnetic measurements in the Podunajská nížina Lowland (12). Neovolcanic rocks are located at relatively large depths and therefore their magnetic manifestation is less pronounced. The exception is Burda (15). The presence of buried volcanoes was also found at Humenné (16) and Zboj (17) (Fig. 3.4).

These anomalies were interpreted in separate papers by Kubeš et al., in Suk, 2002, and by Filo et al., (2003).

The manifestations of Tertiary volcanism products in magnetic maps depend on several factors: magnetic properties, intensity and character of hydrothermal changes, area and vertical dimensions, composition of volcanic complex, morphological conditions and geomagnetic mapping methodology used within individual neovolcanic mountains.

3.6.1 Magnetic properties of neovolcanic rocks

Within the framework of regional geophysical research of neovolcanites in Slovakia, the study of magnetic properties of rocks on samples taken from natural outcrops and selected boreholes was carried out. Laboratory values of volume magnetic susceptibility (KAPA) and remanent magnetic polarization (Ir) were determined. The greatest interest was focused on the detection of magnetic parameters from Kremnické and Štiavnické vrchy Mts.

From the Geofyzika a.s. data obtained, the magnetic properties of the basic types of volcanic rocks show a wide range of KAPA and Ir values (Table 3.3).

The KAPA values ranged from 0 to 94,137 x 10^{-6} (SI), Ir values range from 0 to 61,896 nT. This great variance of values was also found within individual petrographic types. The variability of the values is conditioned by the basic factors that determine the magnetic properties. They are:

a) the quantity and type of ferromagnetic minerals;
b) the magnetic properties of the individual minerals;
c) the type of minerals distribution in the rock;
d) the type and intensity of hydrothermal processes in the rock.

Tab. 3.3 Magnetic properties of neovolcanic rocks

Rocks	Number of samples	KAPA x 10^{-6} [SI]			RMP [nT]		
		min.	max.	x	min.	max	x
Rhyolites	271	18.84	19,230.62	2,996.82	6.28	9,663,.66	1,127.76
Rhyolite pyroclastics	144	310.23	13,175.44	3,999.10	14.44	2,346.21	299.56
Rhyodacites	25	1,760.91	15,398.56	7,067.51	18.84	1,283.63	241.15
Dacites	10	7,283.54	16,973.58	12,743.38	296.67	3,594.80	1,372.93
Pyroxenic andesites	1,595	89.18	74,480.80	23,789.90	18.84	61,898.19	2,460.13
Hornblende-pyrox. andesites	25	7,443.06	28,437.10	16,844.22	1,458.84	2,559.60	2,200.76
Hornblende-biotit. andesites	215	639.30	47,787.03	16,748.76	10.05	5,319.91	1,307.87
Propylitized andesites	230	0	628.0	100.48	0	251.20	11.30
Pyroclastics of pyrox. andesites	1,802	339.12	44,834.18	10,304.22	18.59	24,586.20	865.76
Basaltic andesites	22	1,369.04	26,398.61	13,367.61	405.94	5,966.88	2,385.27
Alkali basalts, basanites	76	2,135.20	94,137.20	30,990.54	18.97	19,123.86	5,393.64
Pyroclastics of basalt. basanites	31	18.84	8,626.21	4,270.40	2.14	1,501.05	565.58
Quartzose diorite (propylit.)	435	0	43,960.00	12,220.88	0	728.48	242.41

x – mean value

Despite the great variability of the values of the monitored parameters, we can pronounce the basic knowledge of the direct dependence of the magnetic parameters on the basicity of the rocks. From the mean values calculated for the basic types of neovolcanic rocks (rhyolite – andesite – basalt), the KAPA and Ir parameters are increased with the basicity. It has also been found that secondary alterations, which affect the volcanic rocks in particular in the central volcanic zones, significantly impact the values of the magnetic parameters. In many cases, they lead to significant reductions in the values, and from the originally high-magnetic rocks the rocks can become very low-magnetic or practically non-magnetic.

We also consider for practically non-magnetic rocks the Neogene sediments without a volcanic fraction. We include fine-grained volcanoclastics in the low-magnetic rocks. The group of moderately magnetic rocks represent predominantly medium-grained volcanoclastics.

Coarse-grained volcanoclastics, breccias and solid (unbroken and non-metamorphosed) products of andesite volcanism are assigned to a group of magnetic, strongly magnetic or high-magnetic rocks. These include basalt volcanism products.

The results of palaeomagnetic studies in some of the neovolcanic mountains (Kremnické vrchy, Slanské vrchy, Vihorlatské vrchy) proved the existence of volcanic rocks with normal and reverse magnetic polarization. Palaeomagnetic studies use the ability of some rocks to retain their magnetic parameters obtained at the time of their origination, at the time of their conversion to the final (so far last) state. The study results give the possibility to decode the polarization of the Earth's magnetic field in its geological history along with information on the time course of the alternation of the Earth's magnetic field's normal and reverse polarity.

The results of palaeomagnetic and isotopic studies in East Slovakian neovolcanites and the analysis of polarities of volcanic complexes by aeromagnetic maps (Gnojek & Kaličiak, 1990) provide good information for confrontation with the latest magnetostratigraphic scale.

This magneto-stratigraphical scale allows to specify the age of volcanic rocks (in order of 10^{-2} Ma).

From the magnetostratigraphic scale it follows that a series of inversions emerged during the Miocene. The normal polarities prevailed in the Late Badenian and in the Pannonian, in the Early and Middle Badenian and in the Late Sarmatian (till the beginning of the Pannonian) reverse polarity prevailed. The Early and Middle Sarmatian is a period with an equal representation of both polarities. The longest duration (almost 1 million years) had a reversed polarity period in the Middle Badenian (16.20 to 15.23 Ma). All other periods were clearly shorter than 1 Ma.

The basic and background material for the incorpration of the Neogene volcanic rocks into a magneto-stratigraphical scale are the latest geological knowledge, radiometric age and polarization of objects according to the results of geomagnetic mapping.

3.6.2 Interpretation of magnetic anomalies generated by the products of Tertiary and Quaternary volcanisms and interpretation of volcanic complex thicknesses

We have already mentioned two important factors that greatly influence the overall character of the magnetic field in the neovolcanic mountains. These are the magnetic properties of rocks (rock complexes) and the presence of products with normal and reversed magnetization.

Reverse magnetization rocks are represented by negative magnetic anomalies. The largest presentation they have in Pohronský Inovec, Kremnické vrchy, Štiavnické vrchy, Javorie, Slanské vrchy and Vihorlatské vrchy Mts.

The value of the anomalies largely depends on the area and vertical dimensions of magnetically active rocks. Small volumes (less than 200 x 200 m) and small thickness (less than 30 m) of volcanic rocks may not display a real anomaly in airborne measurements even though their presence has been proven by geological mapping. On the contrary, in several cases we have found anomalies that we interpret as the effect of volcanic rocks of larger dimensions, covered by non-magnetic younger sediments of different thicknesses (e.g. anomalies in Žiarska kotlina Basin, southern and SE part of the Štiavnické vrchy Mts., in the western part of the Slanské vrchy Mts.).

Magnetically active volcanic rocks, in the vast majority of cases, build morphological elevations with different orientation and with different positions in the direction of aeromagnetic profiles. The mutual position of morphostructures and measured profiles has a great effect on the overall character of the magnetic field anomalies. The most optimal image of the anomalous effect of surface and near-surface sources provide measurements along profiles oriented perpendicular to the direction of the mapped morphostructure. The distortion of the anomalous effect of the morphostructure occurs in cases where the profiles are oriented to the structure at oblique angles. The most complicated are the anomalous effects of volcanic complexes oriented in parallel with the orientation of the profiles. With such a case, we meet, for example, in the southern and SE part of the Javorie Mountains.

For the above reasons, the magnetic anomalies were interpreted not only based on the results of geological mapping, but also on the topographic documents at scale 1 : 50,000. The purpose of confronting magnetic and topographic maps was to eliminate as much as possible the impact of the relief on the orientation, amplitude and polarity of the interpreted anomaly or groups of less-extensive anomalies.

Particularly pronounced is the deformed character of the anomalies in the highly dissected terrain, i.e., where there is a rapid change of relief. Typical features of this type of relief are narrow backs, steep slopes and deeply incised river valleys.

Based on the mutual relationship of real positive and negative anomalies of ΔT to terrain relief, we have defined sites where volcanic rocks with normal (positive anomalies) or reversed (negative anomalies) magnetic polarization predominate. Separated locations by polarization type are indicated in the magnetic anomaly sources map at a scale of 1 : 50,000 (Kubeš et al. 2001).

Virtually in all the above-mentioned neovolcanic mountain ranges have been implemented terrestrial profile magnetic measurements, mainly aimed at solving metallogenic problems in the central volcanic zones and in their immediate vicinity.

The territory of Central Slovakian Neovolcanites Field was covered by aeromagnetic measurements with an average flight height of 80 m above the terrain (Gnojek & Janák, 1986), 500 m above the terrain and 2,000 m above sea level (Šalanský, 1970). The results of the measured data were displayed on the ΔT anomaly maps (scale 1 : 50,000). The measured values at different altitude levels provide information about the magnetic field changes in the vertical direction.

The nature of the change in ΔT with observation level was analysed at locations where magnetically active volcanic rocks are well defined by geological mapping and drilling results. It has been shown that the relatively smallest decrease in ΔT values with altitude occurs in places where the magnetic volcanic complex has larger area dimensions and reaches relatively larger thicknesses. Above the volcanic complex of smaller area dimensions and smaller thickness, there is a significantly more pronounced decrease in ΔT values with increasing the altitude of the observation level.

Small-dimensional bodies with relatively large depth ranges (necks, dykes, stockworks, etc.) are displayed in intrusive anomalies in terrestrial measurements, but their appearance is not observable in aeromagnetic maps.

In the interpretation of the thicknesses of the volcanic complex, we proceeded from the geological knowledge of the horizontal to sub-horizontal placement of the lower edge of magnetically active rocks over practically non-magnetic sediments without volcanic fraction or only with low content of magnetic minerals (fine-grained volcanoclastics – tuffs and tuffites).

From the analysis of the relationship between geological objects, terrain relief and changes in ΔT values at three height levels (1 m, 500 m and 2,000 m), we found that a magnetically active volcanic complex with a thickness of 100 m produces an anomalous effect in height of 500 m average amplitude 40 nT. This means that, for example, to a magnetic anomaly that reaches a value of 100 nT at 500 m above the terrain, we can attribute volcanic complex with a thickness up to 200 m, to the value up to 200 nT the thickness of up to 500 m, the value up to 400 nT the thickness of up to 1,000 m.

Similarly, the thicknesses of the volcanic complex of Slanské and Vihorlatské vrchy Mts. were interpreted. This was based on the results of aeromagnetic measurements with a flight height of 300 m above the relief (Beneš, 1971). It has been found that a 100 m volcanic complex produces a 300 m anomalous effect of about 70 nT, with a thickness of 500 m around 350 nT and 1,000 m about 700 nT.

The data obtained from the analysis of the magnetic field values at a height of 300 m and 80 m above the terrain were supplemented by information obtained from measurements with a flight height of 500 m and 80 m. From the statistical processing of the values of anomalies at sites measuring 300 m and 80 m above ground relief (East Slovakian neovolcanites), or at a height of 500 m and 80 m above the relief (Central Slovakian neovolcanites), it is known that a 100 m thick volcanic complex is displayed at a height of 100 m above the relief with a magnetic anomaly with an amplitude of about 125 nT. To solve the amplitude relation of the ΔT anomaly to the thickness of the complex, we considered several facts that affect the overall character of the anomaly, but especially its average value. It must be borne in mind that in such morphologically complicated conditions the flight height was 80 m strictly maintained and ranged from 60 to 140 m above the ground. In this case, it is necessary to consider the significant influence of surface local magnetic inhomogeneities on the shape and amplitude of the magnetic anomaly, especially in the morphologically dissected environment. The third important criterion for the interpretation of thicknesses is the step of the ΔT in the aeromagnetic maps used, which is not always constant.

In the area of Central Slovakian neovolcanites, the maps of ΔT were constructed with an interval: 0, ±20, ±50, ±100, ±200, ±300, ±400, ±500, ±750 and ±1,000 nT.

In the area of East Slovakian neovolcanites, the interval was chosen: 0, ±10, ±30, ±50, ±70, ±100, ±150, ±200, ±250, ±300, ±350, ±400 and ±500 nT.

In order to solve the relation of the anomaly amplitude to the thickness of the volcanic complex, we used the intervals of ΔT values from both regions (Table 3.4). At the same time, we added data on min. or max. thickness of the volcanic complex. With regard to all problems associated with the quantitative interpretation of magnetic anomalies in such complex geological and morphological conditions, the interpreted data should be considered as more or less indicative. Their refinement requires the use of data from other geophysical methods, e.g. gravimetry and vertical electrical sounding results (VES).

Tab. 3.4

Anomalies ΔT [± nT]			**Interpreted thicknesses of volcanic complex [m]**		
min	**max**	**x**	**min**	**max**	**x**
10	50	30	30	50	40
50	100	75	50	70	60
100	200	150	70	130	100
200	300	250	130	200	160
300	500	400	200	400	300
500	750	625	400	600	500
750	1,000	875	600	800	700

x – mean value ΔT [nT] x – mean thickness [m]

3.7. Conclusions

The Department of Geophysics at SGIDŠ succeeded in supplementary measurement of the geomagnetic field of Slovakia in recent years and to create a unified database of geomagnetic measurements. The created database has allowed for the interpretation of significant magnetic anomalies and their geological significance. We also used the database for the uniform interpretation of geomagnetic anomalies, which contributed mainly to the clarification of the geological structure in all regions of Slovakia and to the creation of geological maps at a scale of 1 : 50,000. The MGII maps are inseparable part of this work. New geomagnetic measurements have also revealed the presence of buried neovolcanites of Pokoradzská tabuľa Plateau, Cerová vrchovina Upland, Lučenská-Rimavská kotlina Depression, Podunajská nížina Lowland, etc. In the north-eastern Slovakia, buried neovolcanites with reversed magnetism at the Zboj Village were found. Different types of granitoid rocks in the vicinity of the Vysoké Tatry, Malé Karpaty, Tribeč, and Veľká Fatra Mts. have been distinguished, since these more basic granitoid differenciates (tonalites) are manifested in the magnetic field by slightly increased values of the total induction of the geomagnetic field. The results of geomagnetic measurements have also contributed to determining the area extent of Vepor Stratovolcano. Geomagnetic measurements can be used especially in neovolcanic mountains, where the lava flows of andesites with their tuffs and tuffites positions (tuffs and tuffites appear in the magnetic field as weak magnetic) are alternating frequently.

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4. Monitoring the Volumetric Activity of Radon in the Geological Environment of the Slovak Republic

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Abstract: Natural radionuclides and products of their radioactive decay are omnipresent in all the compartments of our environment. The radon volumetric activity in ground air, waters and above tectonics has been monitored in the Slovak Republic for several decades under umbrella of the geological task of the State Geological Institute of Dionýz Štúr "Partial Monitoring System of Geological Factors, Subsystem 05 – Monitoring of Radon Volumetric Activity". The several ten years of observations enable to distinguish long-term and short-term variations of radon content in selected sites and environs across Slovakia. The seasonal variations of the radon volumetric activity doesn't depend solely upon humidity and gas permeability of soils and rocks at the given site, but also on geological setting and lithology. The same meteorological conditions, but different geological environ result in different nature of these variations. This contribution presents the results of the radon activity monitoring over a period of 2002–2016, which has confirmed wavy or sinusoidal dependence in the radon bulk activity variations.

Keywords: radon; radioactive decay; radon volumetric activity; radon variations

4.1 Introduction

The human population is permanently exposed to the effects of different types of radiation. However, the issue of natural but also artificial (induced) radioactivity has been virtually "taboo" for decades. Uranium was a strategic raw material for the nuclear (arms, energy) industry, and the results of survey and scientific research in this area (particularly during the so-called "Cold War") were strictly classified. Health risks and impacts on the population have largely been degraded, and it has often been argued that radon and its nuclear decay products directly threaten miners in uranium mines.

Concerns and attention of the public have long been focused on artificial sources of radiation (nuclear weapons, nuclear power, health, etc.), with the most of the population not even knowing that the most significant irradiation (beyond the periods after nuclear experiments, accidents, etc.) is generated by natural sources (Figure 4.1).

The impact of exposure to radon abroad is dealt with by several reputable institutions (e.g. UNSCEAR – *United Nations Scientific Committee on the Effects of Atomic Radiation*, ICRP – *International Commission on Radiological Protection*), but also other organizations and scientific workplaces. Their research has shown that natural sources of radioactive radiation make up nearly three quarters (73 %) of the total radiation burden of the population.

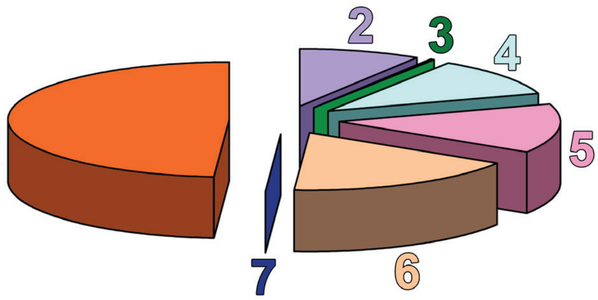

Fig. 4.1 *Radiation burden of the population (source: www.suro.cz) 1: radon (48.9 %), 2: natural radionuclides in the human body (8.9 %), 3: Chernobyl fallout (0.3 %), 4: medical exposure (10.9 %), cosmic (13.9 %), 6: gamma radiation from Earth (17.0 %), 7: others (0.13 %) – of which nuclear power plant output equals to 0.04 %*

The most important source of natural radiation are radon (^{222}Rn) and radionuclides (^{218}Po, ^{214}Po, ^{210}Tl, ^{210}Po,...) arising within its nuclear decomposition. These are adsorbed in the human airway where lung tissue cells are irradiated at the contact, which can ultimately lead to the development of malignant carcinoma.

Various studies have shown that the likelihood of lung cancer increases with the increasing concentration of radon and its decay products, but also with the duration of exposure. The fact that radon is the second most important cause of lung cancer after smoking is also recognized by the World Health Organization which classified it in 2009 in the class 1A carcinogen.

The results of newer epidemiological studies have shown that exposure to radon results in other forms of health damage such as vascular and digestive disorders. The likelihood of health damage is apparently significantly higher than originally assumed.

This has led the European Commission (EC), the International Commission on Radiological Protection (ICRP) and the World Health Organization (WHO) to reconsider health risk from radon exposure.

The European Commission has also defined new requirements to increase the protection of the population from the adverse effects of ionizing radiation – the elaboration of legislation aimed at protecting the population and the introduction of radon programmes in which population awareness is among the priorities.

In Slovakia, since the early 1990s, much more attention has been devoted to natural radioactivity and the risk of exposure to radon from the geological environment when maps of natural rock radioactivity (concentration of potassium – **^{40}K**, equivalent uranium – **eU**, equivalent thorium – **eTh**, total natural radioactivity – **eUt**, dose gamma radiation power – **Da**), radon risk forecast maps volume activities of radium ^{226}Ra and radon ^{222}Rn), radon ^{222}Rn in the ground air, and natural radioactivity in groundwater and surface water maps (U_{nat} = ^{234}U, ^{235}U and ^{238}U isotope concentration). Monitoring of short-term (seasonal) and long-term changes in radon content in the geological environment had not been the focus of solved tasks and no more attention had been paid to variations in radon volumetric activity (RVA; also term radon bulk activity, RBA, is used).

Since the project *"Partial Monitoring System of Geological Factors (PMS GF)"* has been solved, the solvers of the subsystem *"Monitoring of Radon Volumetric Activity in the Geological Environment of the Slovak Republic"* started to systematically address the issue in the whole Slovak Republic.

4.2 Characteristic of the topic in question

A whole range of natural radionuclides and their nuclear decay products are permanently present in all environmental compartments, i. e. in the rocks, in the waters and in the air. The radon (isotope ^{222}Rn – source of alpha radiation with a half – life of 3.825 days) is an inert natural radioactive gas generated by the spontaneous disintegration of ^{226}Ra (alpha and gamma radiation source) in the disintegrating range of uranium ^{238}U and belongs to the so-called rare gases. It has a higher density than air, is very well soluble in water (up to 51% of its volume), it is colourless, tasteless and odourless.

The main source of natural radon is the geological environment, i.e. some minerals and rocks, as well as groundwater flowing through rocks with increased uranium content. Due to the half – life of maternal elements (^{238}U = 4.47 **x** 10^9 years, ^{226}Ra = 1,600 years), the geological environment ensures its continuous supply.

The radon is relatively easy to penetrate through the rock environment and spreads through by diffusion or a convective flow. The diffusion is influenced by physical properties of the environment – especially porosity and moisture. The transport of the radon by convection is higher in order and is caused by the changes in the physical conditions of the environment (temperature and pressure gradients). The most significant manifestation of convection is over the tectonically disturbed zones, which provide good communication paths for gases.

In the free environment, radon is rapidly diluted with atmospheric air, but it can accumulate in high, health-harmful concentrations in confined spaces.

In designing the RVA monitoring within the territory of Slovakia one of the important criteria was a selection of appropriate sites. It was based on an analysis of the results of earlier geological research works dealing with natural radioactivity (e.g. exploration for radioactive raw materials) as well as on newer data and background data obtained from the assessment of geological factors of the environment.

Monitoring of RVA changes in ground air is focused on areas with confirmed elevated (moderate and high) radon risk. Most sites are located in the Spišsko-gemerské rudohorie Mts. area, which has the highest number of sites with high concentrations of soil radon and it is also a region with numerous occurrences of uranium mineralization, including uranium deposits.

The selection of sites for the purposes of soil radon activity measurements on reference areas (RA) was preferably focused on town residential areas: Bratislava (locality Vajnory), Banská Bystrica (Podlavice locality), Spišská Nová Ves (Novoveská Huta and Teplička) and Hnilec.

The soil radon over the tectonics has long been monitored at the Grajnár site, which has been disrupted by the

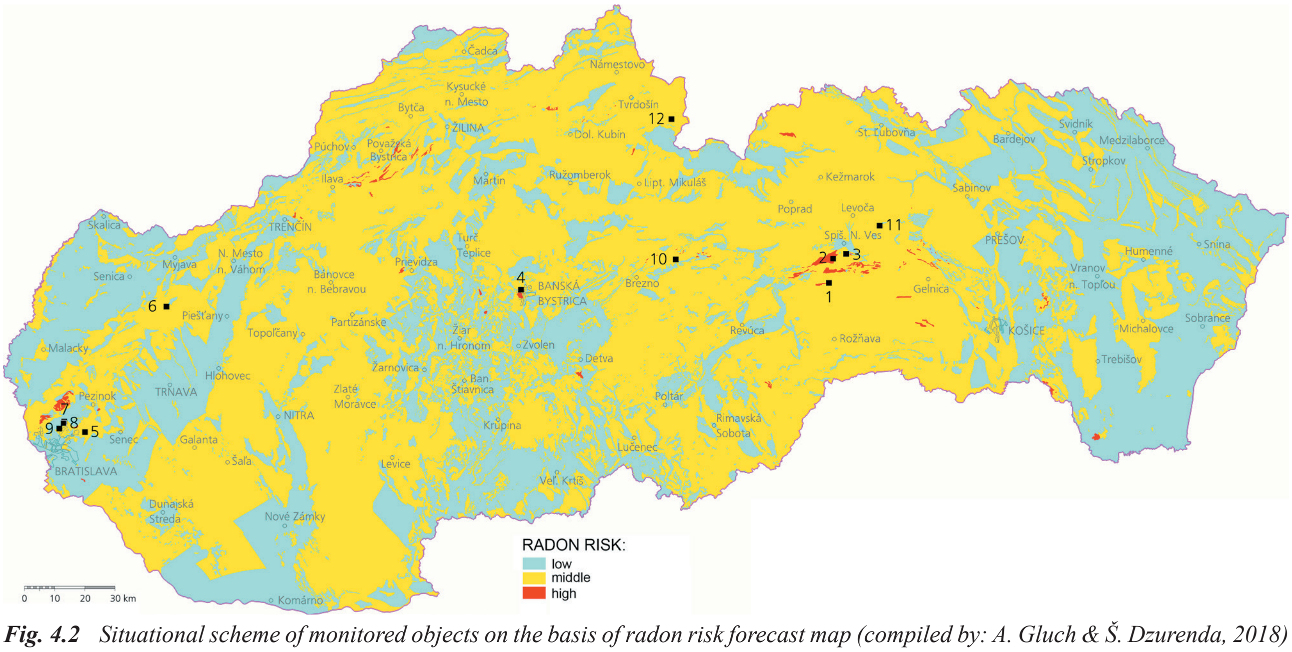

Fig. 4.2 Situational scheme of monitored objects on the basis of radon risk forecast map (compiled by: A. Gluch & Š. Dzurenda, 2018) 1: Hnilec; 2: Novoveská Huta; 3: Teplička; 4: Podlavice; 5: Vajnory; 6: Dobrá Voda, tectonics; 7: spring Himligárka; 8: spring Zbojníčka; 9: spring Mária; 10: spring of Božena Němcová; 11: spring of St. Andrew; 12: spring area Jašterčie

extensive mining and storage of wood in the locality. Since the 2012 season, the work centre has been moved to the Dobrá Voda area (Trnava District).

The assessment of changes in radon concentrations in groundwater is carried out on objects (available springs, exits, etc.), which have been found in previous works to have increased Rn contents, or high volumetric activities of radon – the area of the Malé Karparty Mts. (springs Mária, Zbojníčka and Himligárka), Bacúch (spring of Božena Němcová), Spišské Podhradie (spring of St. Ondrej [*spring of St. Andrew*]) and Oravice (the spring OZ – 1).

The monitoring of several sites had been discontinued, interrupted or partially modified as a result of the malfunction of the monitoring sites by unpredictable anthropogenic activities (earthworks, construction, pollution by wild landfills, etc.).

From approximately three tenths of the objects that have been monitored for the past two decades 12 objects have been monitored to-date for soil radon (one of them above tectonic), and six objects for radon in groundwater (Figure 4.2).

4.3 Methodology

The goal of RVA monitoring in the geological environment is to document and evaluate short-term (seasonal) and long-term (of the order tens of years) changes in radon concentrations in the rock environment (ground air) and groundwater.

A set of geophysical works and activities carried out on objects in the last 15 seasons (period 2002–2016) represents the repeated sampling and measurement of RVA in field and laboratory conditions in the 12 localities (Figure 4.2) within the territory of Slovakia, including their comprehensive processing, evaluation and alignment of results with previous periods, preparation of individual evaluation reports, updating of resulting databases, etc.

The radon in ground air is monitored at each site within the reference area (RA), which consists of individual points (ground sampling probes) arranged in the profiles, or in an irregular network, up to 400 m^2. The essential number of points within RA is 17 probes (16 base measurement probes plus one control probe), representing the minimum statistical set to evaluate radon risk RA within each monitoring date.

The ground air for RVA determination is taken through the hand-driven probes from a depth of about 80 cm. The air sample is sucked into the de-emanated and evacuated scintillation Lucas Cell (LC – Calibrated Scintillation Detector, 125 ml volume) which is then transported for measurement in the laboratory conditions. While sampling the ground air besides the data necessary to determine the RVA value, other additional data are being recorded: weather conditions, precipitation, atmospheric pressure, a qualitative assessment of the moisture content of the sediment in the RA area, the drilling/driving resistance of the probes and soil abstraction.

Groundwater samples for the determination of ^{222}Rn bulk activity are collected in glass ground-neck samplers, full-filled (volume ca 300 ml), without air bubble. At sampling, the instantaneous value of water and air temperature, source yield, atmospheric pressure, meteorological conditions at sampling, including the data required for RVA calculation, are measured.

Under laboratory conditions, radon from each sampler is bubbled through the washer into four de-emanated and evacuated LCs with a volume of 600 ml which are then measured by a calibrated measuring device in a procedure consistent with RVA measurement in ground air. In order to rule out a random error, two samples are always measured, the resulting radon content being their arithmetic mean. The third sample is analysed, provided the pair of measurements exceeds 10 %.

The method of determination of RVA in ground air and gas permeability of groundwater is determined by approved methodology, which is in compliance with the provisions of Act no. 355/2007 on the Protection, Promotion and Development of Public Health and also in accordance with Decree of MH SR no. 528/2007 laying down the details of requirements for the limitation of exposure to natural radiation.

At RVA determination a calibrated and metrologically validated LUK-4A measuring device (manufactured by RADON v.o.s., Prague, Czech Republic) is used, based on the principle of scintillation detection of alpha particles in Lucas cells.

Measurements of samples of gas mixtures (ground air radon or water sample in admixture with atmospheric air) in the LC are performed under laboratory conditions at 210 minutes after their filling, i.e., after achieving a radioactive equilibrium among ^{222}Rn and its decay products.

The volumetric activity of radon (c_A) in ground air is calculated according to:

$$\mathbf{c_A} = (Nv - Np)/k \text{ x } V \text{ x } (3 \text{ x } t_v \text{ x } e^{-\lambda tr}) \qquad [kBq \text{ x } m^{-3}]$$

where:
- Nv – measured number of pulses of gas mix ture sample in LC for t_v time
- Np – measured count of LC background pulses for t_v time
- k – coefficient of efficiency of the measuring device
- V – sample volume of gas mixture in LC [litres]
- t_v – time of gas mixture sample measurement in LC [sec]
- t_r – time from ground air intake to LC until start of measurement [min]
- λ – decay constant ^{222}Rn

The radon risk of RA is assessed in the sense of the amended MoE Directive (currently under approval) and according to Annex no. 7 to Government Regulation no. 350/2006 where the limits for the determination of radon risk categories are recommended based on a quantitative assessment of the measured RVA in ground air and the permeability of soils for gases (Table 4.1).

Tab. 4.1 Determination of the radon risk category of the reference area

	3rd quartile – RADON VOLUMETRIC ACTIVITY [kBq x m^{-3}]		
RADON	*Gas permeability of soil*		
RISK CATEGORY	*poor*	*moderate*	*well*
low – I	< 30	< 20	< 10
moderate – II	30 – 100	20 – 70	10 – 30
high – III	> 100	> 70	> 30

The gas permeability of local soils and rocks is determined for each RA by a granulometric analysis of the sample taken based on the percentage of fine particles **f** (particle diameter <0.06 mm) as presented in the Table 4.2.

Tab. 4.2 Determination of gas permeability of soils and rocks

Permeability	Fine particles proportion	Class in terms of STN 73 1001
poor	**f** > 65 %	F5, F6, F7, F8
moderate	15 % < **f** < 65 %	F1, F2, F3, F4, S4, S5, G4, G5
well	**f** < 15 %	S1, S2, S3, G1, G2, G3

The gas permeability of local soils and rocks is determined for each RA by a granulometric analysis of the sample taken based on the percentage of fine particles **f** (particle diameter <0.06 mm) as presented in the Table 4.2.

Volumetric activity of radon in water (c_A) is calculated according to the relationship:

$$c_A = (Nv - Np)/k \times Vv \times (3 \times t_v \times e^{-\lambda tr}) \times e^{-\lambda tF} \quad [\text{Bq x l}^{-1}]$$

where: Vv – water sample volume in the washer [litres]

$e^{-\lambda tF}$ = $F(t_F)$ – a coefficient expressing a ^{222}Rn activity decrease over time t_F

Other variables are explained when calculating RVA in ground air.

Decree of the Ministry of Health of the SR no. 528/2007 provides guide values for the implementation of measures (Table 4.3), which are basic indicators when assessing the suitability of the water supplied in terms of natural radioactivity. The parameters set out in this Decree are applied when evaluating the results of RVA determination in waters.

Tab. 4.3 Guide values for the implementation of measures

Type of water supplied	**Total volumetric activity alpha [Bq.l^{-1}]**	**Total volumetric activity beta [Bq.l^{-1}]**	**Volumetric activity 222Rn [Bq.l^{-1}]**
Spring water “appropriate for toddlers nutrition”	0.1	0.2	20
Natural mineral water	1.0	2.0	100
Spring water, packed drinking water, potable water	0.2	0.5	100

4.4 Overview and results of realized works

4.4.1 Ground radon on reference areas (RA)

The RVA monitoring in ground air for RA was performed at the given period (2002–2016) at different frequencies at five locations, the position of which is depicted in Figure 4.2. Overview and comparison of results of the RVA measurements in ground air for individual localities, objects and monitoring seasons is in Table 4.4.

The reference area of Hnilec, located approximately 2.1 km south-east of the centre of the same name on state road no. 533 Spišská Nová Ves – Gemerská Poloma, has long been evaluated in high to extremely high radon risk. The source of soil radon is an enriched medium-coarse-grained *Gemeride* (so-called Hnilec) granite with anomalous uranium content (according to field gamma spectrometry about 20 ppm eU – Čížek, Smolárová & Gluch, 2001). We rank it to the rocks with the highest natural radioactivity in the Western Carpathians.

The monitoring of RVA in ground air here is realized four times a year, every two months, in the early spring to late autumn. The highest mean $RVA_{3.Q}$ (third quartile RVA) values are recorded during the summer/autumn (Figure 4.3). In October 2005, the highest RVA value in a single probe (1,861 kBq x m^{-3}) was measured here, which is the maximum not only for this object, but also – according to the available data – one of the highest values traced on the territory of Slovakia. The RVA in ground air is very variable (3–1,861 kBq x m^{-3} in a single probe), with a long-term average of 468 kBq x m^{-3} and a standard deviation of 292 kBq x m^{-3} (Table 4.4) of the whole set of measurements (1,018 probes).

The reference area Novoveská Huta is located on the southwest side of the same village along the local communal road (from the church towards a local part Rybníky) in an environment built of colourful sandstones and slates of the Stráže Mb. of the Novoveská Huta Fm. (Permian) with connection to the NNE – SSW dislocations.

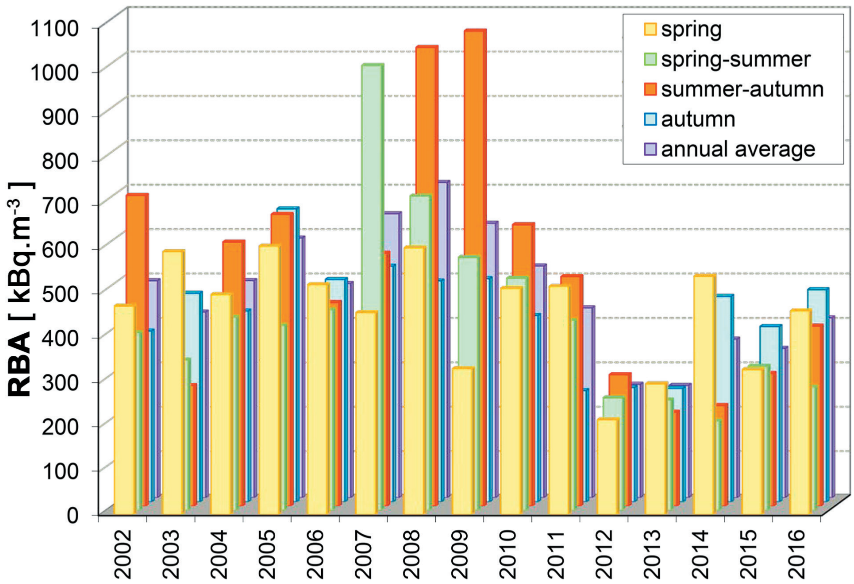

Fig. 4.3 *RVA monitoring in ground air, 2002–2016, RA Hnilec*

The course of variations of RVA in ground air at the RA Hnilec in individual seasons shows a certain "wavy" character. While RVA correlates well with low precipitation totals (RVA_{2003} = 420 kBq x m^{-3} or RVA_{2011} = 430 kBq x m^{-3}), the opposite case is not fully demonstrated. Although the local maximum $RVA_{3.Q}$ from the 2005 season (587 kBq x m^{-3}) corresponds to the increased rainfall, but for the exceptionally damp year 2010 this is no longer valid (source: www.shmu.sk; Table 4.4). After the peak in the 2008 season (712 kBq x m^{-3}), the $RVA_{3.Q}$ values in the soil in recent years show a rather significant drop to up to 255 kBq x m^{-3} from 2013 (trend $RVA_{2013/2008}$ = 0.36).

(The monitoring of RVA in ground air is usually carried out 6–8 times during the year, at monthly intervals from the early spring to late autumn periods. During the summer months, high concentrations of soil radon are recorded in this territory (Figure 4.4). The maximum RVA in a single probe was recorded here in July 2006 (670 kBq x m^{-3}).

After the 2006 $RVA_{3.Q}$ peak of 2006 (113 kBq x m^{-3}) there was a significant decrease in soil radon concentration to 35 kBq x m^{-3} in the 2013 season ($RVA_{2013/2006}$ = 0.31, Table 4.4). However, in a very dry year 2011 (656 mm pre-

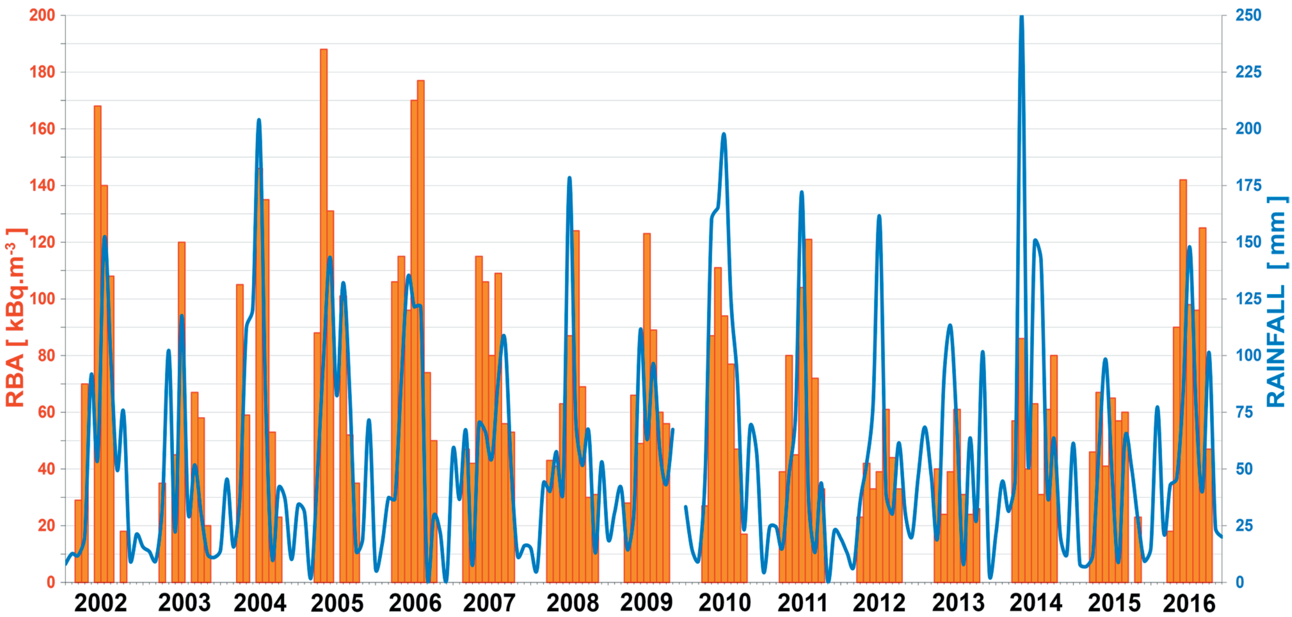

Fig. 4.4 *RVA monitoring in ground air, 2002–2016, RA Novoveská Huta*

cipitation totals) there was a slight increase in soil radon concentrations ($RVA_{3.Q}$ = 71 kBq x m^{-3}).

Important and significant results of soil radon monitoring at this locality include the observed phenomenon of a sharp decline in RVA (sometimes up to low risk), which is reflected on RA Novoveská Huta under the same conditions – during the first frosts in the autumn, possibly ground frosts in the spring (with non-frozen soil). Probably as a result of the increased temperature gradient between soil and atmospheric air, the radon leaks more intensely into the atmosphere, resulting in a significant reduction of its content in the cover sediments (Smolárová & Gluch, 2010).

The reference area Teplička is located approximately 2.8 km south of the centre of Spišská Nová Ves in the local part Šulerloch (named after the homonymous altitudinal point 646 m). The RA subsoil is made of Paleogene sediments (slate, sandstone) with a higher proportion of clay fraction.

Monitoring at this site takes place at monthly intervals between early spring and late autumn. Although the object is monitored on the same day as the Novoveská Huta RA, in a distance of about 5 km, the variations in soil radon concentrations have a significantly different course. Elevated values are mostly recorded in spring and autumn and lows in the summer months (Figure 4.5). In the single probe, the highest RVA value (196 kBq x m^{-3}) was measured in May 2005.

The course of variations of soil radon content in RA Teplička within the individual monitoring seasons has a certain "quasi – sinusoidal" shape, with minimum RVA values correlating with low precipitation totals (RVA_{2003} = 56 kBq x m^{-3}, RVA_{2011} = 59 kBq x m^{-3}). After the peak in the 2005 season (92 kBq x m^{-3}), the values of $RVA_{3.Q}$ in ground air since 2006 (except exceptionally damp year 2010) show a rather significant decrease compared to RVA_{2013} = 35 kBq x m^{-3} (Table 4.4). Trend $RVA_{2013/2005}$ = 0.38.

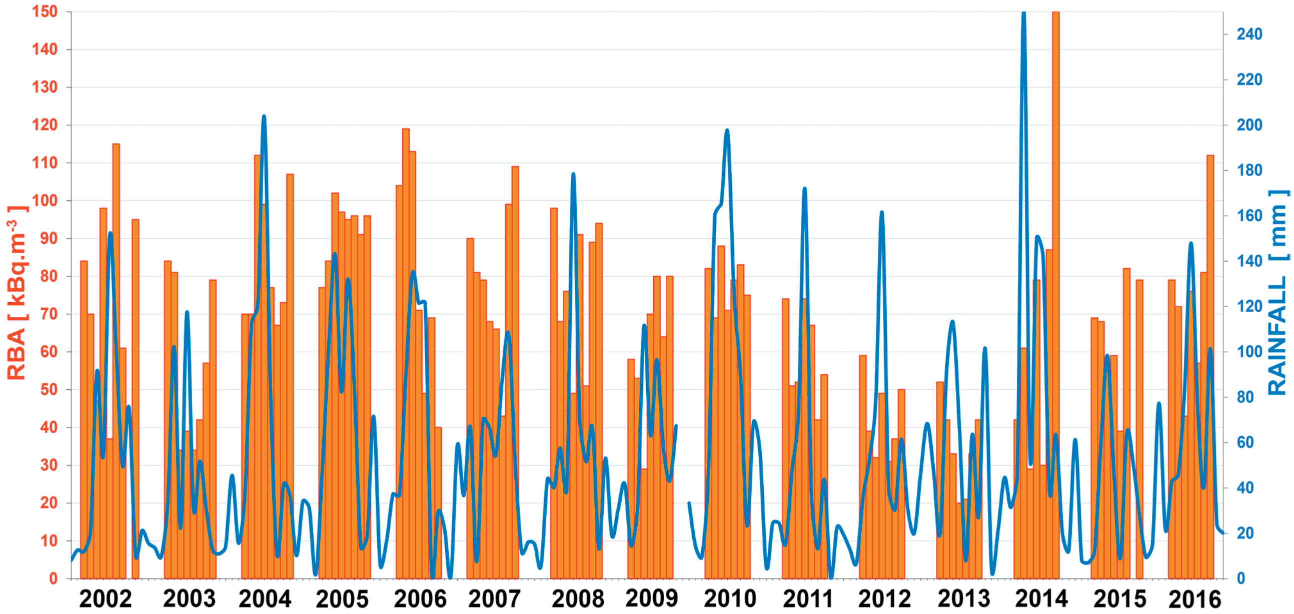

Fig. 4.5 RVA monitoring in ground air, 2002–2016, RA Teplička

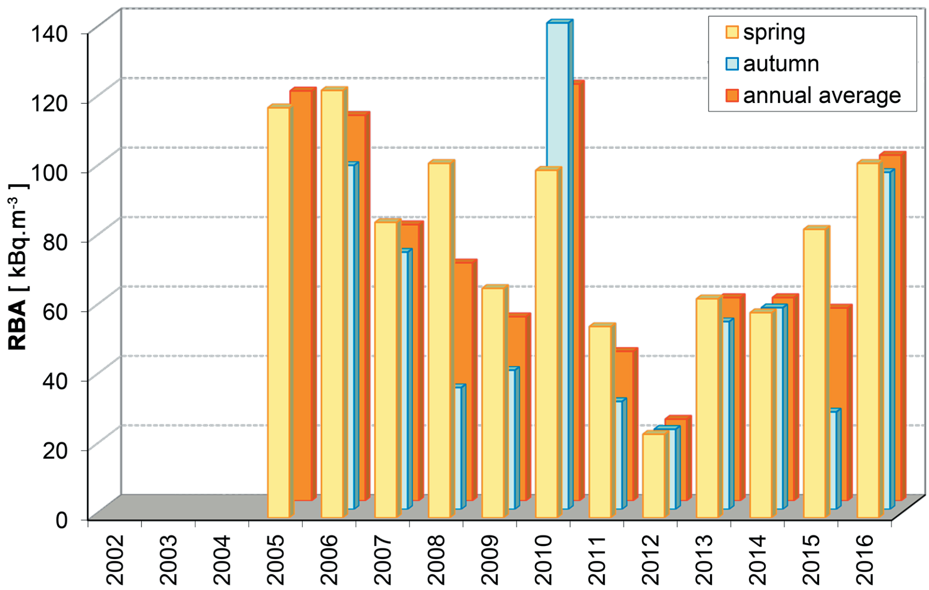

Fig. 4.6 RVA monitoring in ground air, 2005–2016, RA Banská Bystrica – Podlavice

The reference area Banská Bystrica – Podlavice is based on the NW border of Banská Bystrica (part Podlavice), along both sides of the field road near the gardeners' colony.

The RA lithology forms Ramsau Dolomite with anomalous concentrations of uranium (so-called "uranium dolomites"). The RVA monitoring in ground air was carried out twice during the year (spring and autumn).

Since the 2005 season ($RVA_{3.Q}$ = 118 kBq x m^{-3}) – exception is the exceptionally damp season of the year 2010 – this object has manifested a gradual and significant decrease to RVA_{2012} = 24 kBq x m^{-3} (trend $RVA_{2005/2012}$ = 0.20), observable especially in autumn monitoring (Figure 4.6). The highest radon content in the ground air in a single probe (272 kBq x m^{-3}) was found in May 2006.

The reference area Bratislava – Vajnory is situated on the north-eastern edge of a homonymous part of Bratislava, along the meliorating channel of approximately N – S direction.

The lithology of the object form relatively well gas-permeable fluvial sediments. Monitoring of RVA in ground air in the area of the RA Bratislava – Vajnory is realized from the 2005 season twice a year (spring and autumn). In the period 2005–2011 (with the exception of the exceptionally wet season 2010), the average annual levels of RVA (Figure 4.7) decreased gradually and significantly ($RVA_{2011/2005}$ = 0.46). In a single probe, the maximum content of soil radon (122 kBq x m^{-3}) was recorded in May 2005.

Limit levels of $RVA_{3.Q}$ in ground air were recorded here in the seasons 2010 (69 kBq x m^{-3}), or 2012 (19 kBq x m^{-3}), trend $RVA_{2012/2010}$ = 0.28.

In the 2013 season, RVA measurements in the ground air were performed on the DV–2 geophysical profile, located about 80 m NW from the DV–1 profile. The gasometry was performed simultaneously with electrical resistivity tomography (ERT) with a 5.5 meter measurement step. The monitored failure zone was also indicated on this profile by a significant increase in soil radon concentrations with RVA_{MAX} = 20 kBq x m^{-3} compared to the normal range of approximately 1 kBq x m^{-3}, as well as by a significant drop in the resistance level from over 3,000 ohm.m in poorly disintegrated Wetterstein Dolomite up to a value below 300 ohm.m above the tectonic dislocation.

In the 2014 and 2015 seasons, detailed measurements of soil radon concentrations on P– or P–2 (each with 6 emanometric profiles, network of 5 x 10 m), located in the vicinity, or south of the emanation anomaly traced in 2012 at the DV–1 profile. The disturbance zone on the P–2 area was manifested by anomalous increase of the soil radon concentrations RVA_{MAX} = 48 kBq x m^{-3}, in the normal range of approximately 7 kBq x m^{-3}.

In season 2016, a detailed radon survey continued SSE towards P–3 area – five emanometric profiles in the 2–5 x 5–10 m (according to terrain accessibility). The monitored disturbance zone has been indicated to date by the highest soil radon content – RVA_{MAX} = 62 kBq x m^{-3}, in the normal field below 10 kBq x m^{-3}.

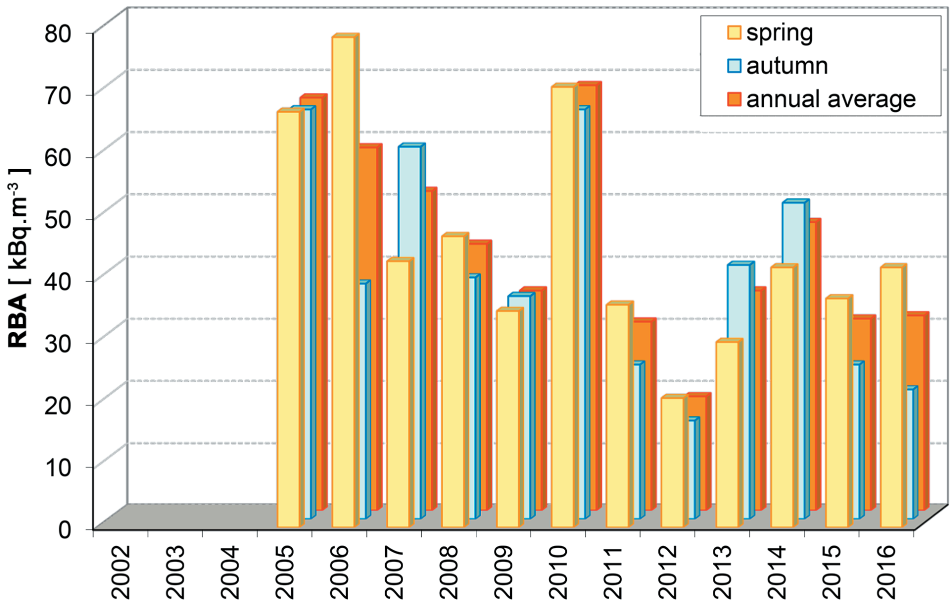

Fig. 4.7 *RVA monitoring in ground air, 2005–2016, RA Bratislava – Vajnory*

4.4.2 Ground radon on tectonics

The first indicative emanation measurements at the **Dobrá Voda site** were realized in the 2012 season on the DV–1 profile, based approximately 1.1 km NNW of the centre of the Dobrá Voda Village. The profile was of approximately NE – SW direction, of a length of 80 m, picking step 5 m (Figure 4.8).

The failure zone, observed in Wetterstein Dolomite (Middle Triassic), covered by fluvial flood-plain sediments, resulted in a significant increase in soil radon concentration with RVA_{MAX} = 24 kBq x m^{-3} compared to the normal field below 2 kBq x m^{-3}.

The area of the failure zone in the Dobrá Voda area (Figure 4.8) is clearly manifested by the increase of the concentrations of radon in the ground air. The resulting tectonic dislocation positively affects the transport of radon to the subsurface parts even from greater depths, so that the soil radon contents reach anomalous values, radically exceeding the background.

After obtaining the necessary instrumentation for the continuous measurement of the RVA and the construction of a monitoring facility (observation well), we assume the future interconnection of PMSGF subsystems 05 (radon volumetric activity) and 02 (Tectonic and seismic activity of the area).

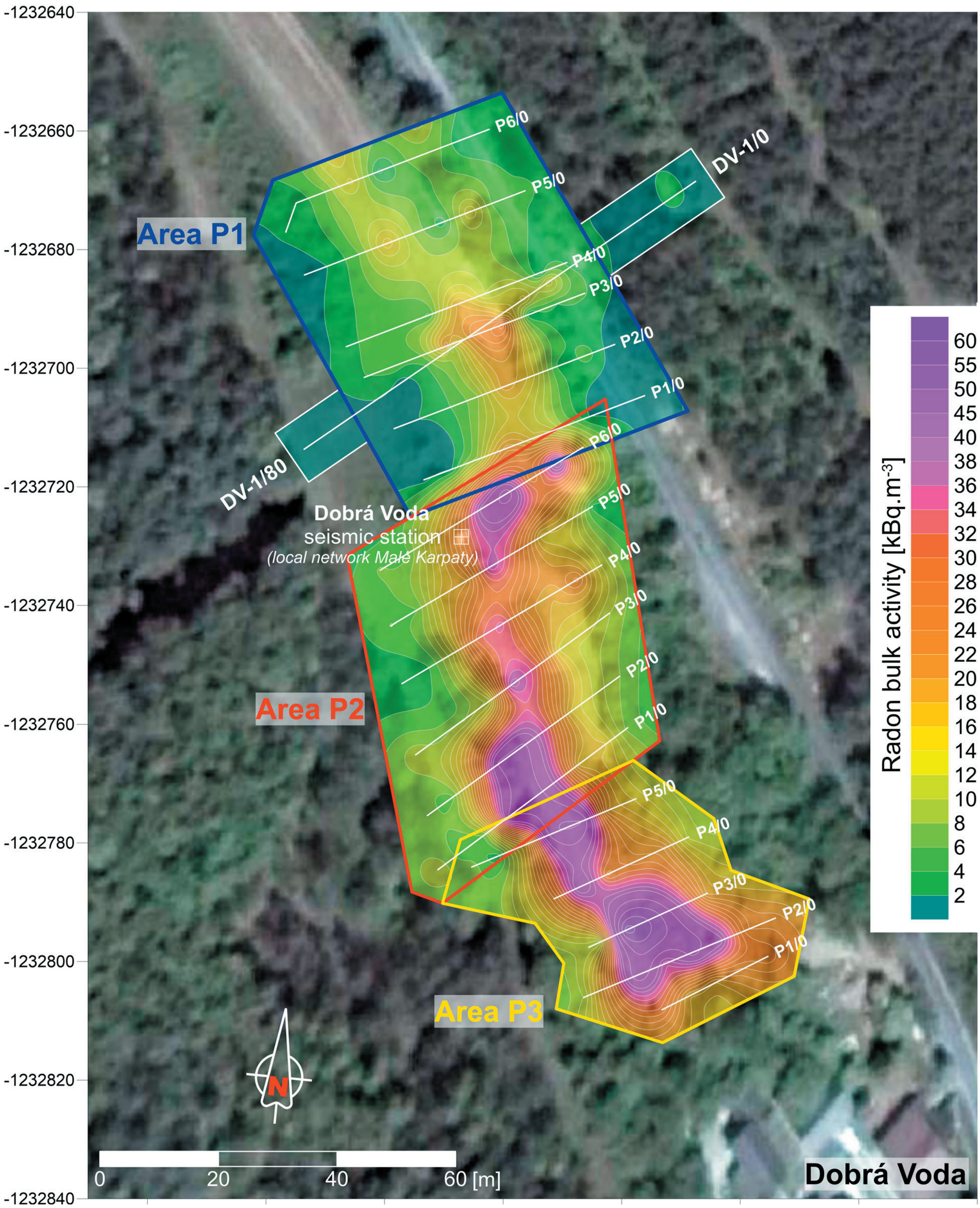

***Fig. 4.8** RVA in ground air above tectonics, period 2012 – 2016, site Dobrá Voda*

4.4.3 Radon in groundwaters

Radiohydrochemical sampling and monitoring of RVA in groundwater was carried out at different frequencies in six locations (Figure 4.2) between 2002 and 2016. The overview and comparison of radon concentration measurements in groundwater by individual localities, objects and monitoring seasons is documented in Table 4.4.

In the area of the Malé Karpaty Mts. (about 9 km north of the centre of Bratislava), the sources of Himligárka, Zbojníčka and Mária (spring of Mary) are monitored twice a year (spring and autumn). Captured and reconstructed springs are related to the acidic environment of the Malé Karpaty Mts (crystalline (leucocrate, muscovite and two-mica granites, granodiorites, of the Bratislava type).

The groundwaters here have a shallow circulation with a link to the zone of disintegration in which conditions for the formation and spread of radon are favourable.

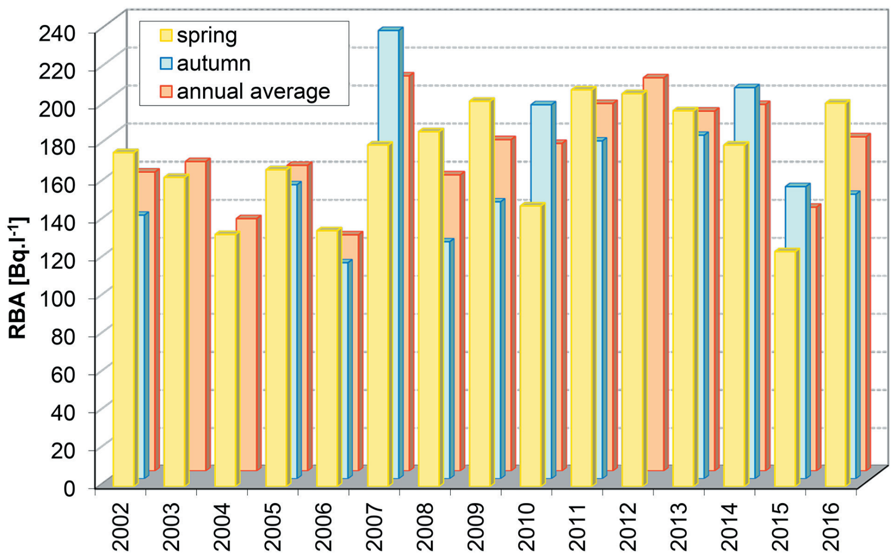

Fig. 4.9 *RVA monitoring in groundwater, period 2002–2016, spring Himligárka (Malé Karpaty Mts.)*

The spring of Himligárka is situated about 30 m from the so-called. Štefánikova magistrála (important tourist route through Slovakia, labelled in red) and about 600 m NNE from the Horný Červený Kríž altitudinal point.

Increased concentrations of ^{222}Rn are recorded mostly in the spring; decreased in autumn. However, the highest radon content (236 Bq x l^{-1}) was measured in the 2007 autumn measurement (Figure 4.9). The yield of the spring varies widely between 0.01 and 1.86 l x s^{-1} while in the autumn of 2004 and 2012 the spring was even dried.

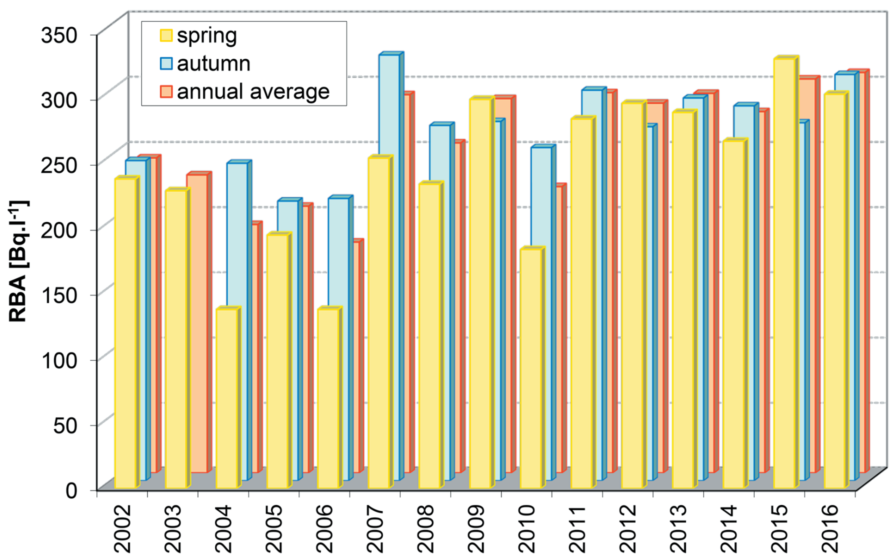

Fig. 4.10 *RVA monitoring in groundwater, period 2002– 016, spring Zbojníčka (Malé Karpaty Mts.)*

The spring Zbojníčka is situated about 800 m from the source of Himligárka and about 270 m west of the Horný Červený Kríž altitudinal point.

As a rule, higher volumes of radon activity are recorded in autumn, with a maximum RVA (330 Bq x l^{-1}) found in the spring of 2015 (Figure 4.10). The yield of the spring is varied in the range of 0.04 to 3.33 l x s^{-1}, while the spring was dried in 2003.

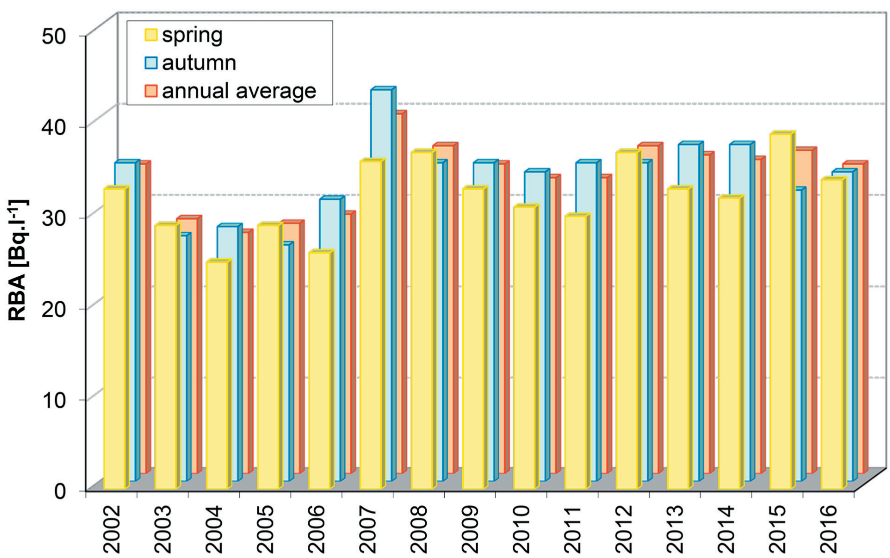

Fig. 4.11 *RVA monitoring in groundwater, period 2002–2016, spring Mária (Malé Karpaty Mts.)*

At the spring of Mária, about 2 km southwest of the Zbojníčka spring, there are long recorded relatively low contents of ^{222}Rn, in the long-term average slightly higher in autumn monitoring. The highest RVA level (43 Bq x l^{-1}) was measured in the autumn 2007 (Figure 4. 11). The yields of the source fluctuate in the range of 0.03 to 1.82 l x s^{-1}.

The spring of Božena Němcová, located approximately 1.4 km north of the centre of Bacúch (Brezno District), was monitored 6–8 times a year in the period under review. Captured and engineered spring object emerge to the surface in the environment of garnet two-mica gneisses and mica schists. The radon is bound here to fault tectonics and to disintegrated, emanation-positive zones of the geological environment.

In the water of the given source were found increased to high levels of radium ^{226}Ra (monitored in the period 1998–2000), which were not stable and varied in the range of about 0.5–1.8 Bq x l^{-1} without correlation to ^{222}Rn concentrations in water.

The radon content during the last 15 seasons was very variable and ranged from 165 to 422 Bq x l^{-1}, the highest value being measured in April 2008 (Figure 4.12). The

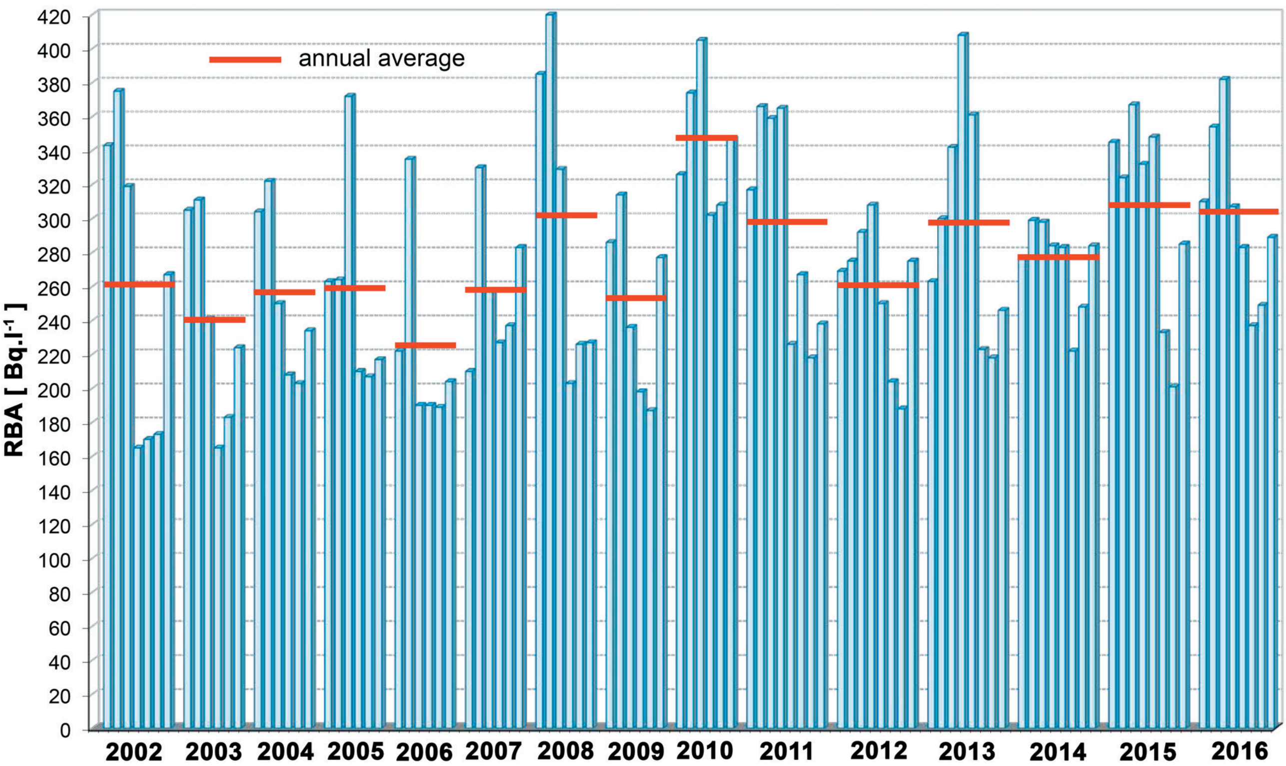

Fig. 4.12 *RVA monitoring in groundwater, period 2002–2016, spring of Božena Němcová (Bacúch)*

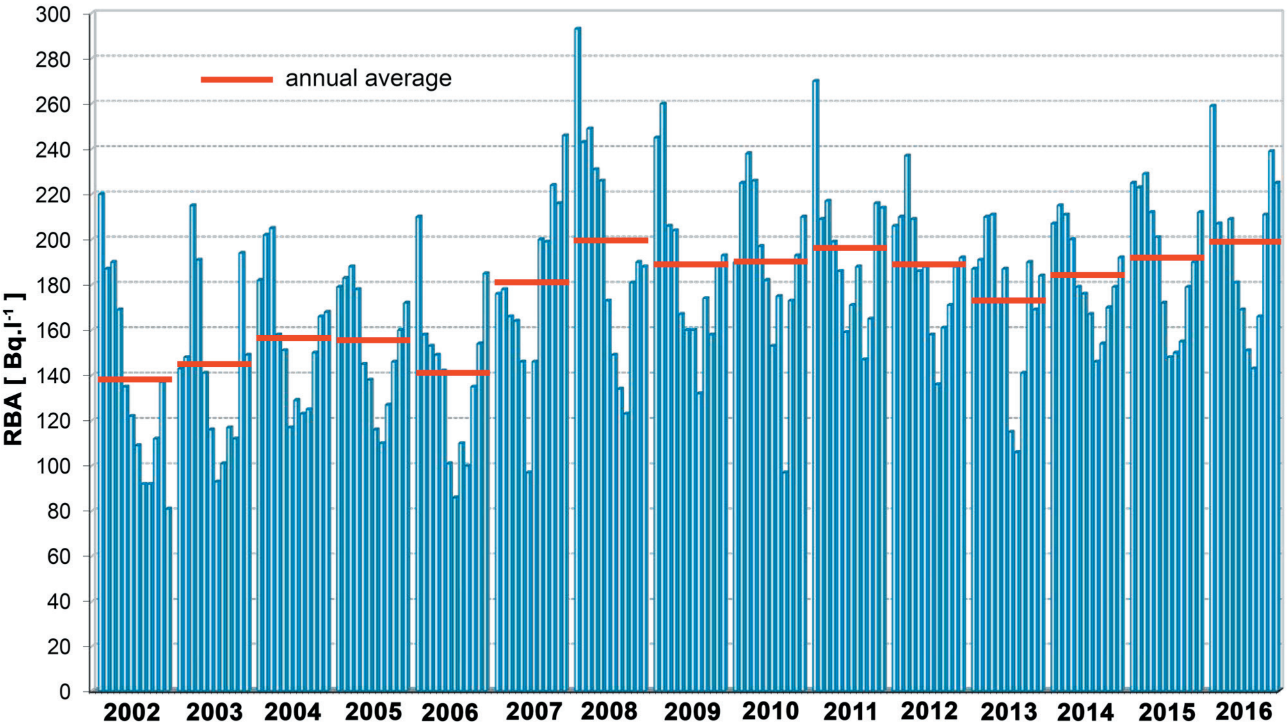

Fig. 4.13 *RVA monitoring in groundwater, period 2002–2016, spring of St. Andrew (Spišské Podhradie)*

variation graph has a relatively regular "sinusoidal" course with RVA maxims at the end of winter (February – April) and minima in summer and autumn months (July – October). The yields of the spring are low but relatively stable in the long run and range from 0.02 to 0.03 l x s^{-1}.

The mineral spring of St. Andrew at Spišské Podhradie, is situated in the area of Sivá Brada on the State Road no. 18 (E 50) Poprad – Prešov. Captured and engineered spring object emerging from travertine mound in an area built of clayey-stony colluvial sediments is monitored 12 times a year at monthly intervals.

Its waters have a deeper circulation and therefore, besides radon, they also have an increased content of ^{226}Ra. We assume that the source area for the radioactivity of these waters is in the base of Triassic carbonates. Like ^{222}Rn in water, also ^{226}Ra concentrations were not stable in the water and during the 1998 – 2001 season they varied between 0.2–1.8 Bq x l^{-1} without correlation to radon contents.

The volumetric activities of radon in the period under review ranged from 81 to 293 Bq x l^{-1} (Table 4.4). The highest RVA was recorded in January 2008 (Figure 4.13). The RVA variation curve has a relatively regular "wave" pattern that repeats throughout the monitored period. Every year, in the winter and early spring (January – April), measured volumes of ^{222}Rn volumetric activity reached up to about three times its minimum contents, measured in summer to autumn (June – September). The yields of the spring are relatively low but stable and in the period under consideration they varied in the range of 0.01 – 0.06 l x s^{-1}.

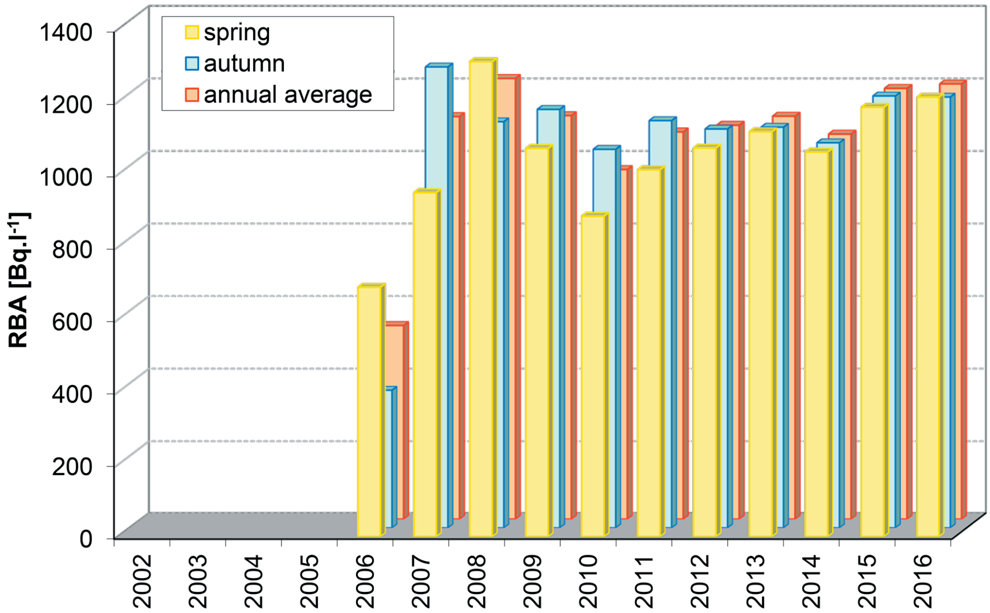

Fig. 4.14 *RVA monitoring in groundwater, period 2002–2016, spring area Jašterčie (Oravice)*

The Jašterčie spring area, located about 1.8 km south of Oravice, is monitored twice a year (spring and autumn). The spring is located about 30 m from the OZ-1 borehole, which (probably due to corrosion and pressure) in 1999 unplugged the shutter at the initial casing section of the borehole, followed by a strong water outlet directly into the spring area. Thanks to this accident, he monitoring had been interrupted until 2006.

The waters of the source in question have a deep circulation, bound to the Pre-Tertiary formations and deep tectonic dislocation zones. Source of ^{222}Rn in groundwater is not only emanative (originating from the environment of emitting rocks), but also autogenic (the resulting dispersion of radium contained in water). The radium contents were monitored by 2000 (volumetric activity of ^{226}Ra was 0.5–1.7 Bq x l^{-1}).

In this natural thermal exsurgence of groundwater – according to available information – the highest RVA in natural groundwater is reached within the entire territory of Slovakia. This is confirmed by the results of the measurements in which the RVA ranged from 382–1,312 Bq x l^{-1} (Figure 4.14). Up to now the highest concentration of ^{222}Rn in water – 1,407 Bq x l^{-1} here was recorded in autumn monitoring in 1998.

Due to the nature of the object – the source with the aged damaged collector object – it is not possible (without relatively difficult technical works) to determine its yield.

4.5 Conclusions

The results of the monitoring of RVA variations in ground air have long been confirmed by the fact that radon concentrations are significantly dependent on meteorological and climatic factors and thus on the moisture and gas permeability of local soils and rocks but to a negligible extent also on the structural and geological setting itself and the lithological characteristics of the rock environment areas of a specific location.

The meteorological conditions in the last 15 monitoring seasons were considerably different for the accumulation and possibilities of radon spreading in the rock environment. It is generally assumed that the moisture content of the cover deposits "positively" influences radon concen-

Tab. 4.4 Course of values of radon volumetric activity (RVA) in ground air and groundwater, period 2002 – 2016

Nr.	SITE	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Long-term average	σ	N
	Ground radon at reference areas	3.Q c_A [kBq.m^{-3}]																	
1	**Hnilec**	491	420	491	587	485	642	**712**	620	524	430	258	**255**	359	334	407	**468**	**292**	**1,018**
2	**Novoveská Huta**	89	58	87	99	**113**	73	61	67	66	71	39	**35**	60	51	88	**70**	**67**	**1,767**
3	**Teplička**	76	56	80	**92**	81	79	77	62	78	59	42	**35**	68	64	74	**68**	**31**	**2,372**
4	**Bratislava – Vajnory**				67	59	52	43	36	**69**	31	**19**	36	47	31	32	**43**	**20**	**408**
5	**Banská Bystrica – Podlavice**				118	111	80	69	53	**120**	43	**24**	59	59	56	100	**74**	**51**	**391**
	Ground radon on tectonics																		
1	**Dobrá Voda, profile DV-1**											6		*)			**6**	**292**	**18**
2	**Dobrá Voda, profile DV-2**												3		*)		**3**	**67**	**60**
3	**Dobrá Voda, area P-1**													10	*)		**10**	**31**	**60**
4	**Dobrá Voda, area P-2**														19	*)	**19**	**20**	**60**
5	**Dobrá Voda, area P-3**															36	**36**	**51**	**37**

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	
Mean precipitation totals in Slovakia in [mm] and [%] of long-term mean	861	**573**	851	938	776	894	860	890	**1,255**	656	747	864	957	719	924	[mm]
	106	**75**	112	125	101	122	112	122	**157**	80	98	122	119	98	124	[%]

Nr.	SITE	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Long-term average	σ	N
	Radon in water	c_A [Bq.l^{-1}]																	
1	**Bratislava – spring Mária**	34	28	**27**	28	29	**40**	36	34	33	33	36	35	35	36	34	**33**	**4**	**60**
2	**Bratislava – spring Zbojníčka**	242	230	191	205	**178**	291	254	288	220	294	284	292	278	303	**308**	**257**	**50**	**60**
3	**Bratislava – spring Himligárka**	158	163	133	161	**125**	**208**	156	175	173	194	207	190	193	139	176	**170**	**32**	**54**
4	**Bacúch – spring of Božena Němcová**	259	238	254	256	**222**	257	299	250	**344**	295	258	295	274	305	301	**274**	**63**	**206**
5	**Spišské Podhradie – spring of St. Andrew**	**137**	143	156	154	140	180	**198**	187	188	195	187	172	183	191	197	**174**	**41**	**365**
6	**Oravice – spring area Jašterčie**					**536**	1,112	**1,217**	1,115	966	1,070	1,088	1,113	1,064	1,190	1,202	**1,061**	**205**	**45**

Note:
3.Q cA mean value of the third quartile RVA in ground air for assessed year
cA mean value of RVA in groundwater for assessed year
σ standard deviation of RVA from all measurements at the site through the entire monitoring period
N number of RVA measurements at the site through the entire monitoring period
the object was not monitored in the given year
*) monitoring was interrupted for the given period of time

trations in the ground air, because the higher humidity of the rock environment more or less effectively slows the penetration of radon to the surface and further into the air. This leads to an increase of its contents in the ground air and vice versa – when the soil humidity decreases, RVA values also decrease. This dependence has manifested itself to a large extent on most monitored sites. The relationship between raising the RVA level in ground air in high precipitation means is unclear, and it will require a longer-term monitoring,

Seasonal variations of RVA in ground air depend not only on the moisture and gas permeability of local soils and rocks, but also on the geological setting itself and the lithological characteristics of the particular site. It follows that, even under the same meteorological conditions, but in different geological settings, the character of variations may not be the same. This knowledge is one of the significant findings in monitoring the variations of RVA in ground air within the geological task solution.

An example of this are the results of the RVA monitoring in the ground air at RA Novoveská Huta and RA Teplička (Paleogene sediments with medium to low gas permeability, with an increased proportion of clay fraction) which are relatively close to each other (about 5 km) practically in the same climatic area but with a different geological profile in which the accumulation and spread of radon are monitored.

Both of these sites were mostly monitored on the same day (i.e. in comparable meteorological conditions) but the results of RVA measurements in ground air show a different course – in the summer months the RA Novoveská Huta recorded increased and the RA Teplička reduced radon content in soil and the opposite behaviour in spring and autumn (Novoveská Huta low and Teplička high RVA).

Among the significant results of the monitoring of radon content in ground air should be included the observed phenomenon of a sharp decline in RVA, which is reflected in RA Novoveská Huta during the first frosts in the autumn, or even ground frosts in the spring. Obviously, due to the temperature gradient between soil and atmospheric air, radon more intensely leaks into the atmosphere and its content in the cover deposits decreases.

The results of RVA monitoring in ground air have long documented the variability of its contents in the surface parts of the rock environment during the year but also over the monitored seasons. The relatively significant dependence of RVA levels on meteorological conditions but with an ambiguous effect on individual localities is confirmed, which is evidently due to their different structural geological and lithological characteristics.

Variations in radon volumetric activity in monitored groundwater sources are of rather seasonal nature and, during monitoring over several seasons, show a certain wavy, “sinusoidal” regularity. Unlike soil radon, they are not so much influenced by random phenomena, changes in the atmosphere and are not so “sensitive” to various short-term weather changes (temperature, atmospheric pressure). Maximum levels of RVA in groundwater are generally recorded in winter and/or in spring and minimum values in summer and autumn months. Neither correlation between ^{222}Rn and ^{226}Ra volumetric activities has been demonstrated on any of the monitored objects, nor was the correlation between source yield and concentration of radon in groundwater samples taken.

Observed tectonic failure zones (localities – Dobrá Voda, Grajnár) are clearly manifested by increasing concentrations of soil radon. The mapped dislocations positively affect the transport of radon to the surface parts even from greater depths, so that the soil radon contents reach anomalous values. From a practical point of view this can be of interest, for example, when observing “active” tectonic dislocations, when there is a high probability of their positive identification even under less favourable conditions.

From the practical point of view, the knowledge gained is of far-reaching importance, because they may lead to considerable underestimation of the radon risk at the building site due to measurements made under inappropriate meteorological conditions (long-term drought, periods with high precipitation, significant temperature differences between the atmosphere and the sediments mainly in the spring, late autumn or winter). A thorough assessment of the geological environment (especially in stratified sediments with increased proportion of clay fraction, the presence of tectonic dislocations, etc.) is also necessary in evaluating the results of these measurements.

The evaluation of the RVA monitoring results in the geological environment is documented by the fact that the variations in its concentrations are both regular (seasonal) and also random (local, time, ...). Gradually collected knowledge on the variability of radon content in rock and groundwater, their evaluation, processing, and availability of monitoring results through Internet services are clearly beneficial to a more objective assessment of radon risk from a geological environment.

More reliable results can be obtained by processing and evaluating long-term monitoring systems, outputs of which can provide relevant background for adopting more general conclusions in this area. This intention is also followed by the implementation of the PMS GF project at the SGIDŠ.

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Act No. 355/2007 of the National Council on Protection, Promotion and Development of Public Health and on Amendments to Certain Acts