Slovak Geol. Mag., 17, 2 (2017), 13 – 24

2. General Maps of Natural and Artificial Radioactivity

Augustín Gluch[1], Štefan Dzurenda[1], Igor Zeman[1]

[1]State Geological Institute of Dionýz Štúr, Mlynská dolina 1, 817 04 Bratislava, Slovakia; e-mail: augustin.gluch@geology.sk

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, Fig. 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 (Fig. 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

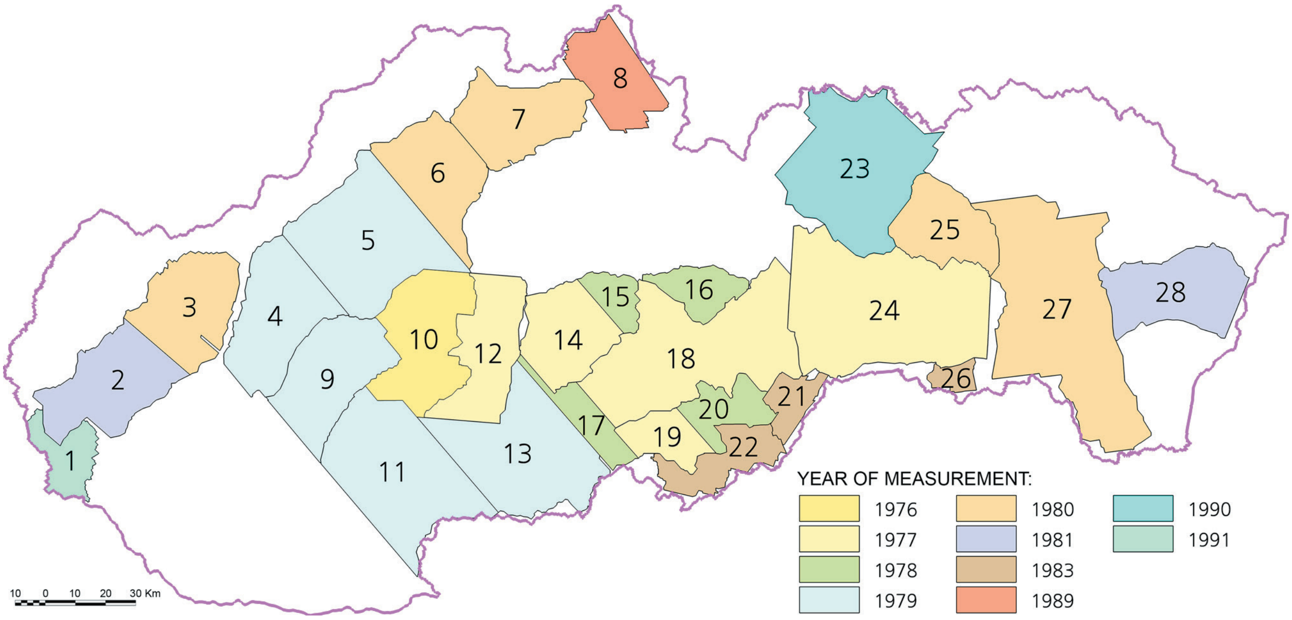


Fig. 2.1 Regional review of the Slovak territory by airborne gamma spectrometry (Kubeš, 2001)
Regions – **1:** Great Bratislava; **2:** Malé Karpaty Mts. – SW; **3:** Malé Karpaty Mts.– NE; **4:** Považský Inovec Mts.; **5:** Strážovská hornatina Mts.; **6:** Martinské hole Mts.; **7:** Malá Fatra and 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.

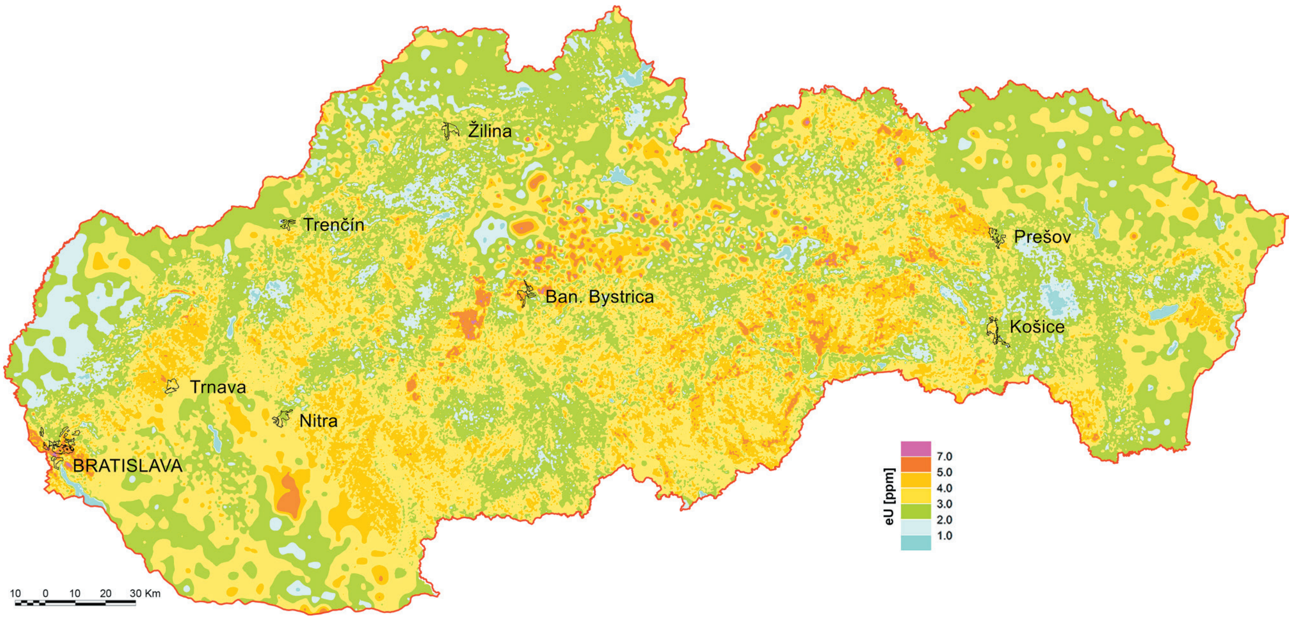


Fig. 2.2 *Concentrations of equivalent uranium eU [ppm] in the territory of the Slovak Republic (Kubeš, 2001), at scale 1 : 500,000*

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 (Fig. 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

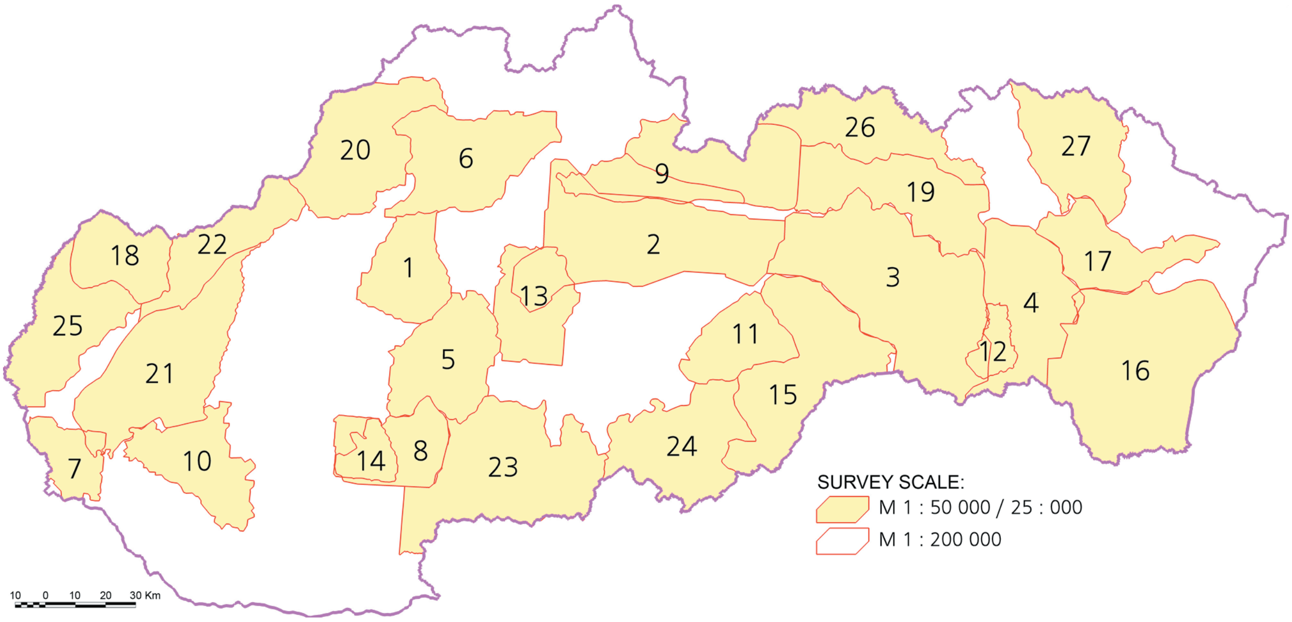


***Fig. 2.3** Regional survey of the Slovak territory by ground gamma spectrometry*
Regions – **1:** Horná Nitra; **2:** Nízke Tatry Mts., Starohorské vrchy Mts., Bystrická vrchovina Upland, Čierťaž; **3:** Hornádska kotlina Basin and E part of the Slovenské rudohorie Mts.; **4:** Košická kotlina Basin 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 (Fig. 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 (Fig. 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 (Fig. 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

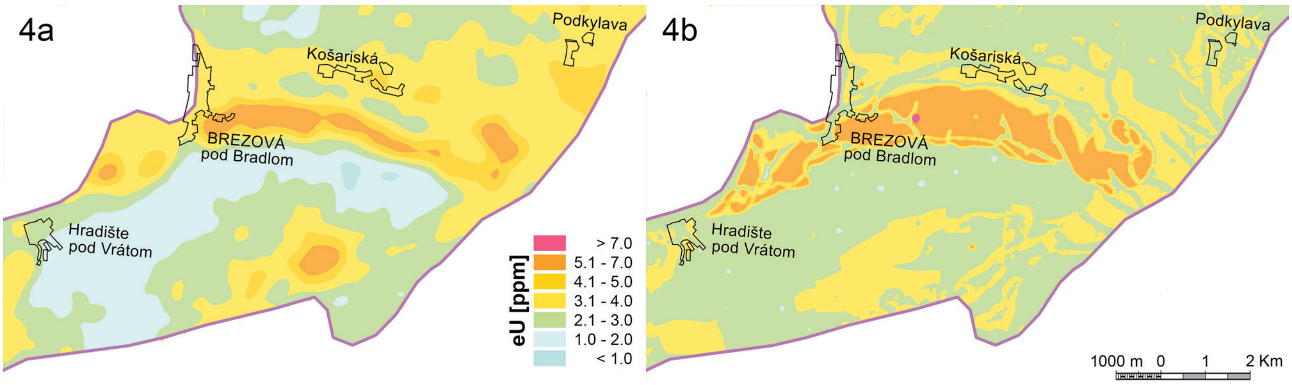


Fig. 2.4 *The options for processing and visualizing GS measurements by standard (4a) and new advanced (4b) interpretation techniques*

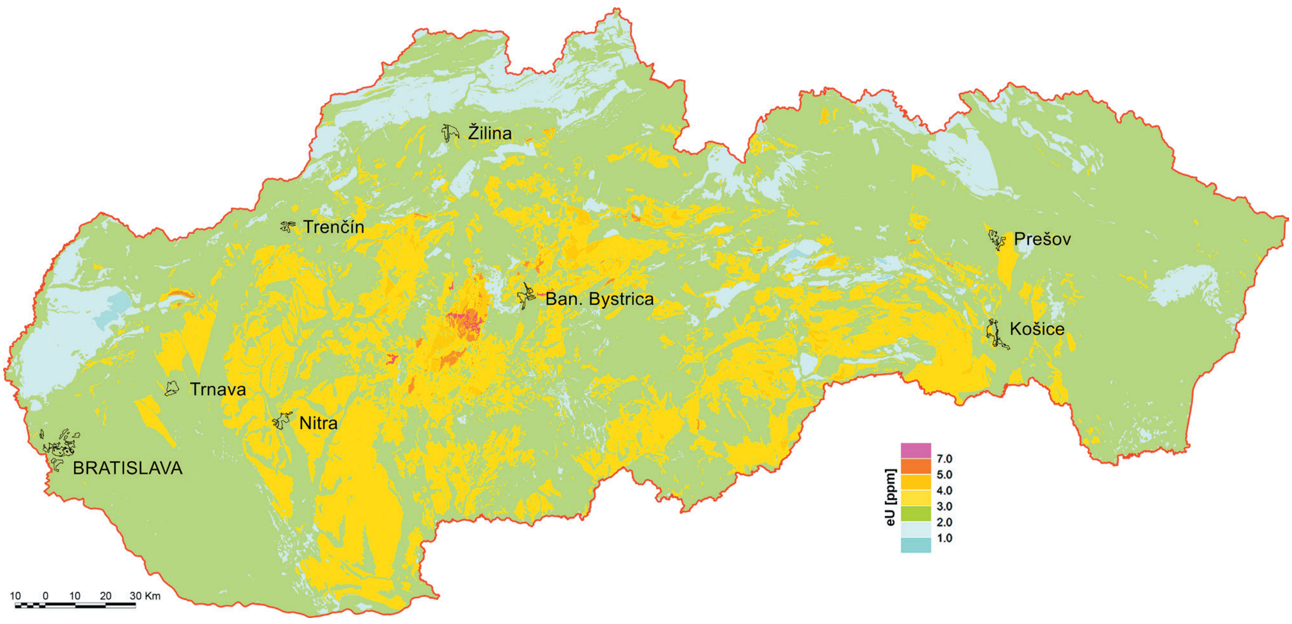


Fig. 2.5 *Concentrations of equivalent uranium eU [ppm] at the SR territory*

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 (Fig. 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.

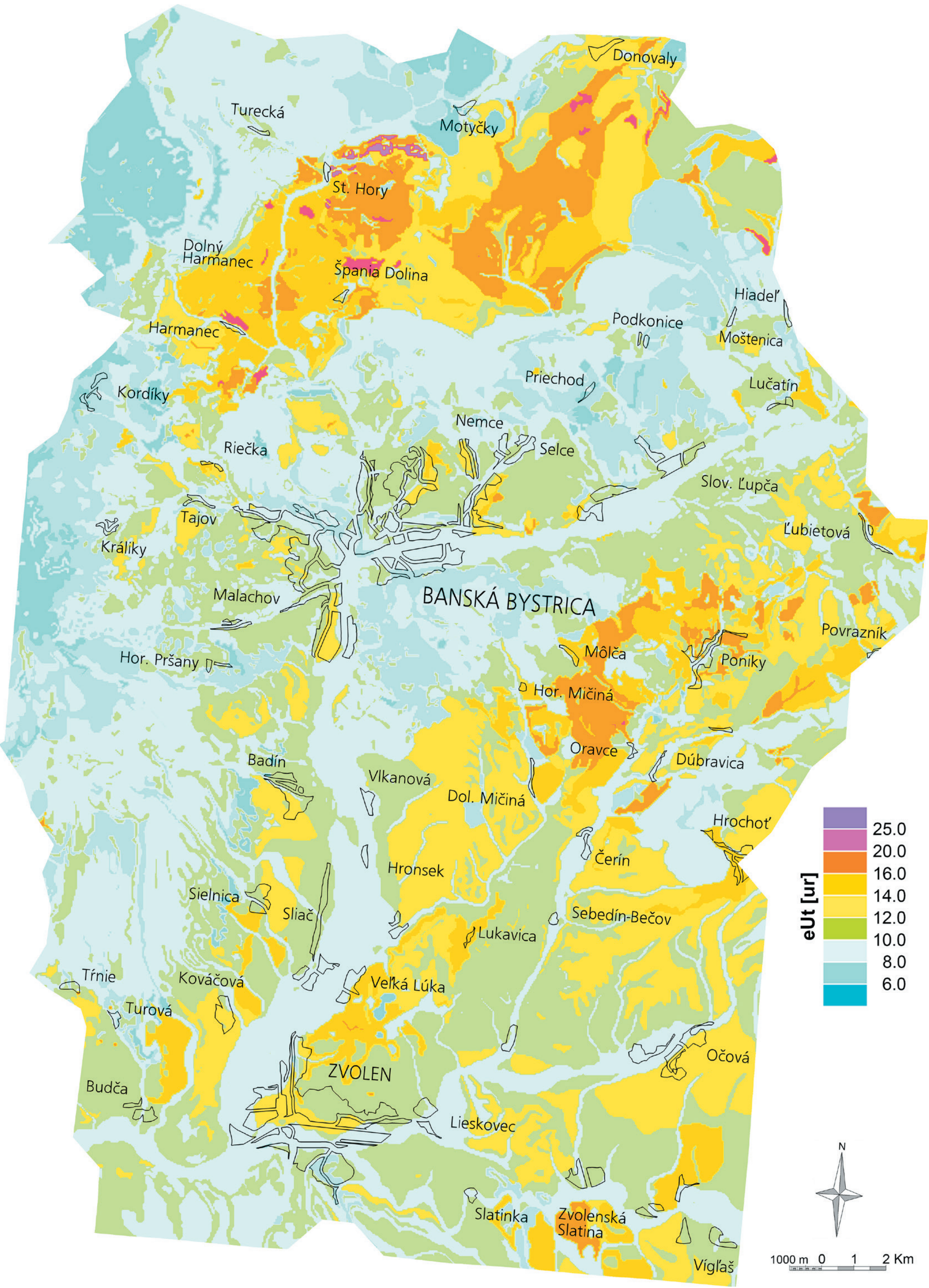


Fig. 2.6 *Total natural radioactivity eUt [ur], region Banská Bystrica – Zvolen, at scale 1 : 50,000*

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 (Fig. 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 (Fig. 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).

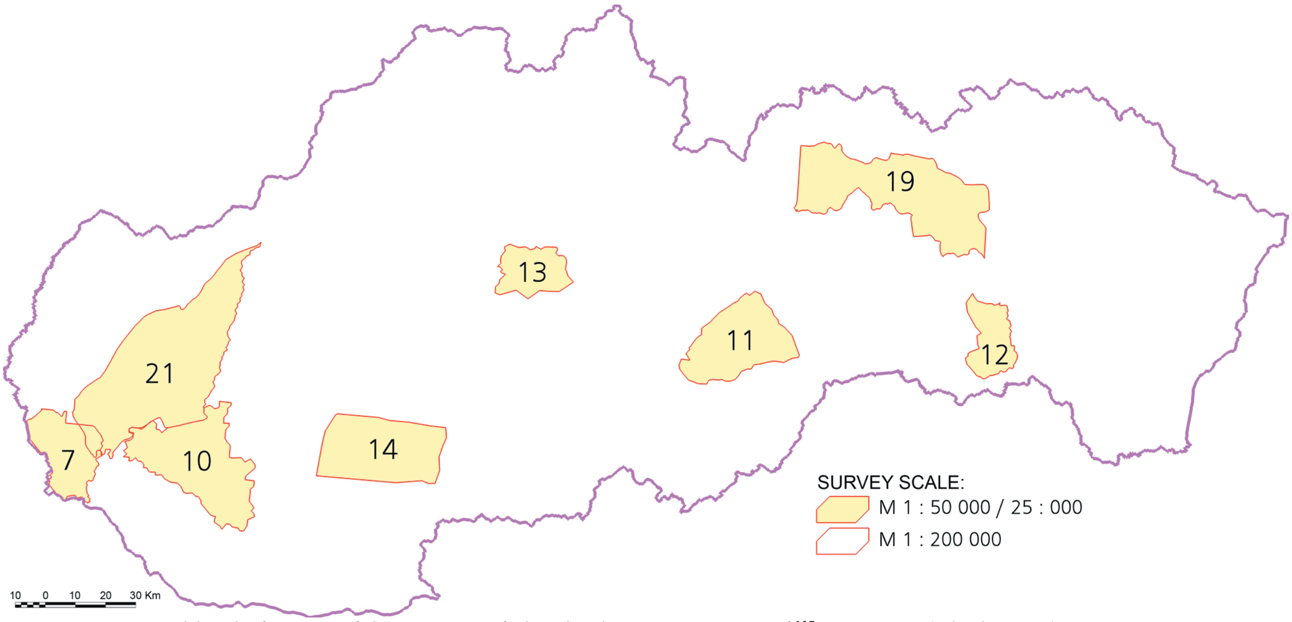


Fig. 2.7 *Regional level of survey of the territory of Slovakia by measurements of ^{137}Cs activity (Gluch, 2005)*
Regions – **7:** Great Bratislava (airborne measurements); **10:** Galanta; **11:** Jelšava – Lubeník – Hnúšťa; **12:** Košice – City; **13:** Banská Bystrica – Zvolen; **14:** Levice – Mochovce; **19:** Poprad and Upper Torysa catchments; **21:** Trnavská pahorkatina Upland

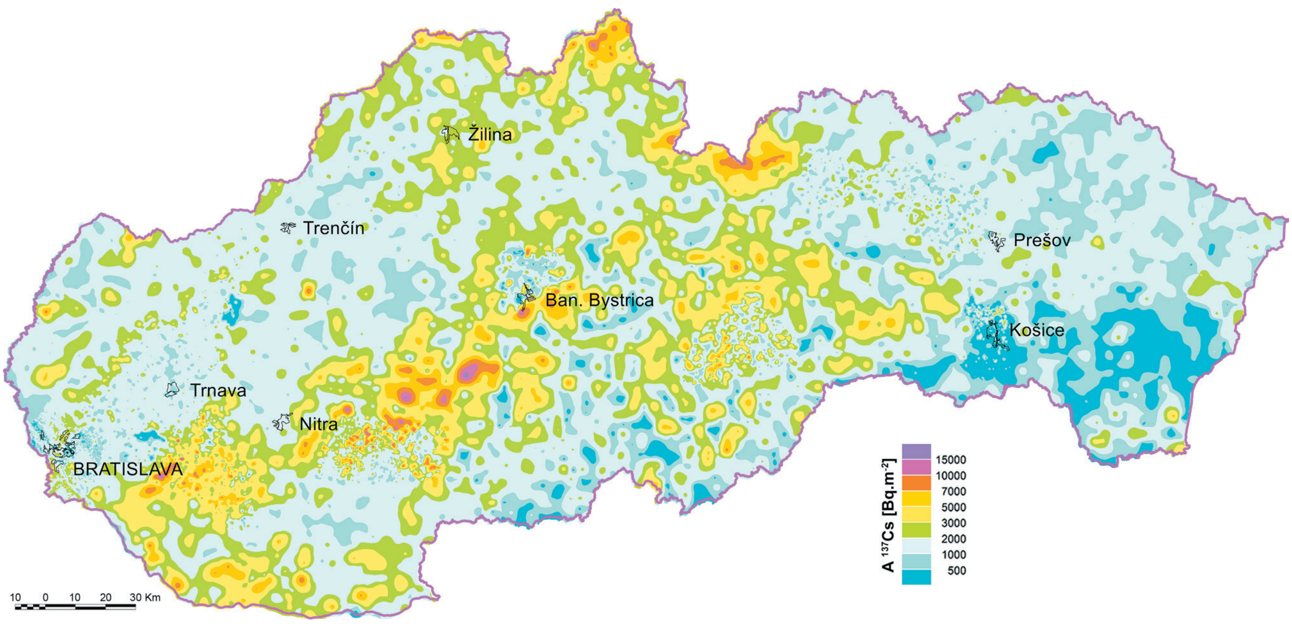


Fig. 2. 8 *Spatial ^{137}Cs activity in the territory of the Slovak Republic as of 01.01.2005 (Gluch, 2005), at scale 1 : 500,000*

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 (Fig. 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 (Fig. 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 (Fig. 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.

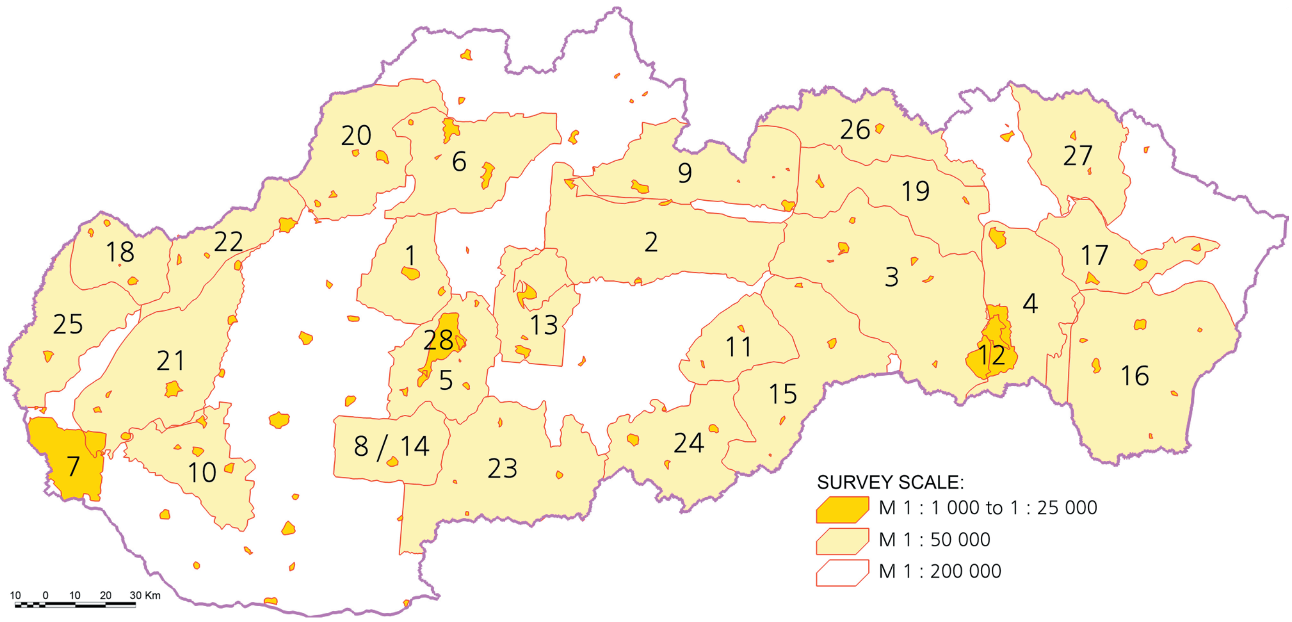
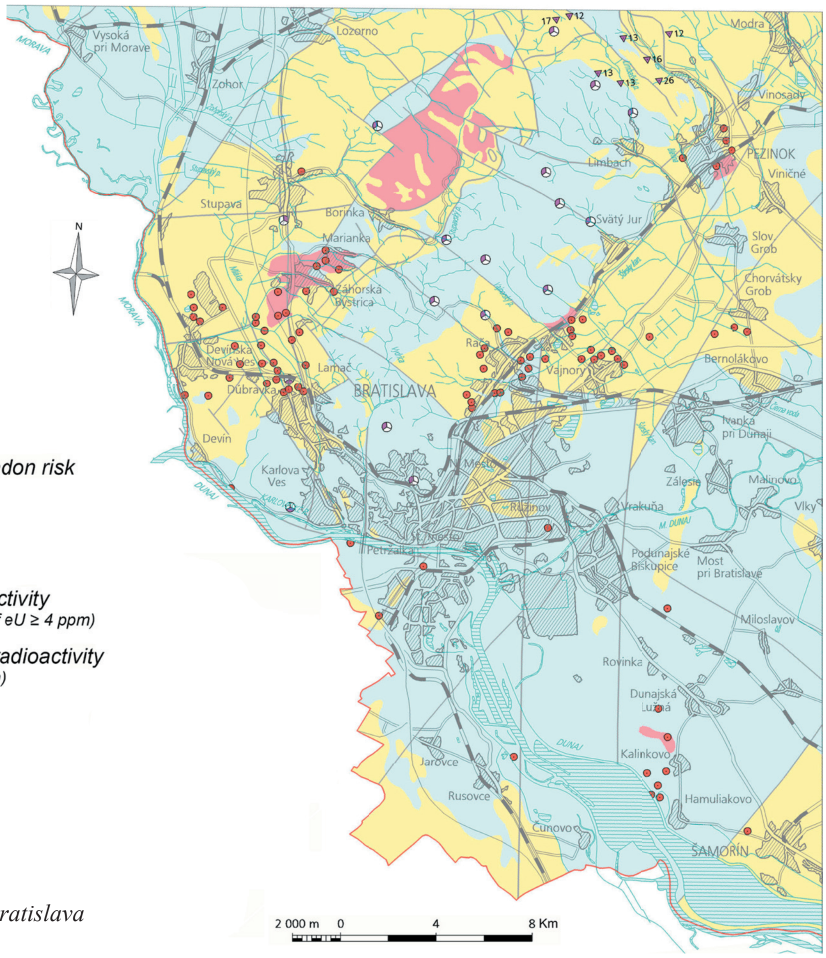


Fig. 2.9 Regional survey of the territory of Slovakia by radon survey
Regions – **1:** Horná Nitra region; **2:** Nízke Tatry Mts., Starohorské vrchy Mts., Bystrická vrchovina Upland, Čierťaž; **3:** Hornádska kotlina Basin and E part of the Slovenské rudohorie Mts.; **4:** Košická kotlina Basin and 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



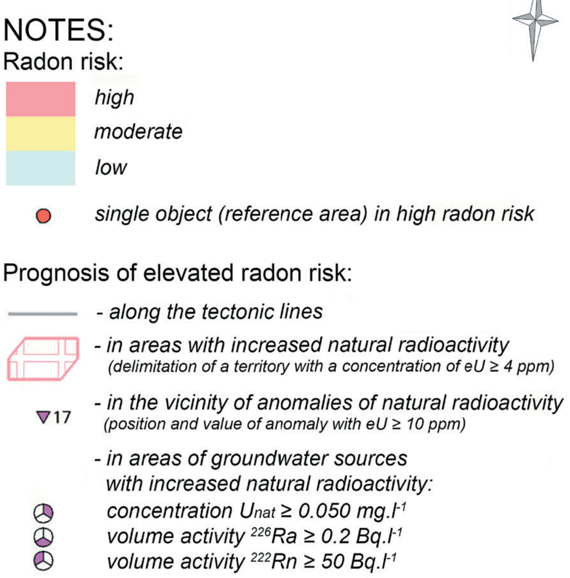


Fig. 2.10 *Radon risk forecast map, sheet 44 – Bratislava (Káčer, 2014), at scale 1 : 200,000*

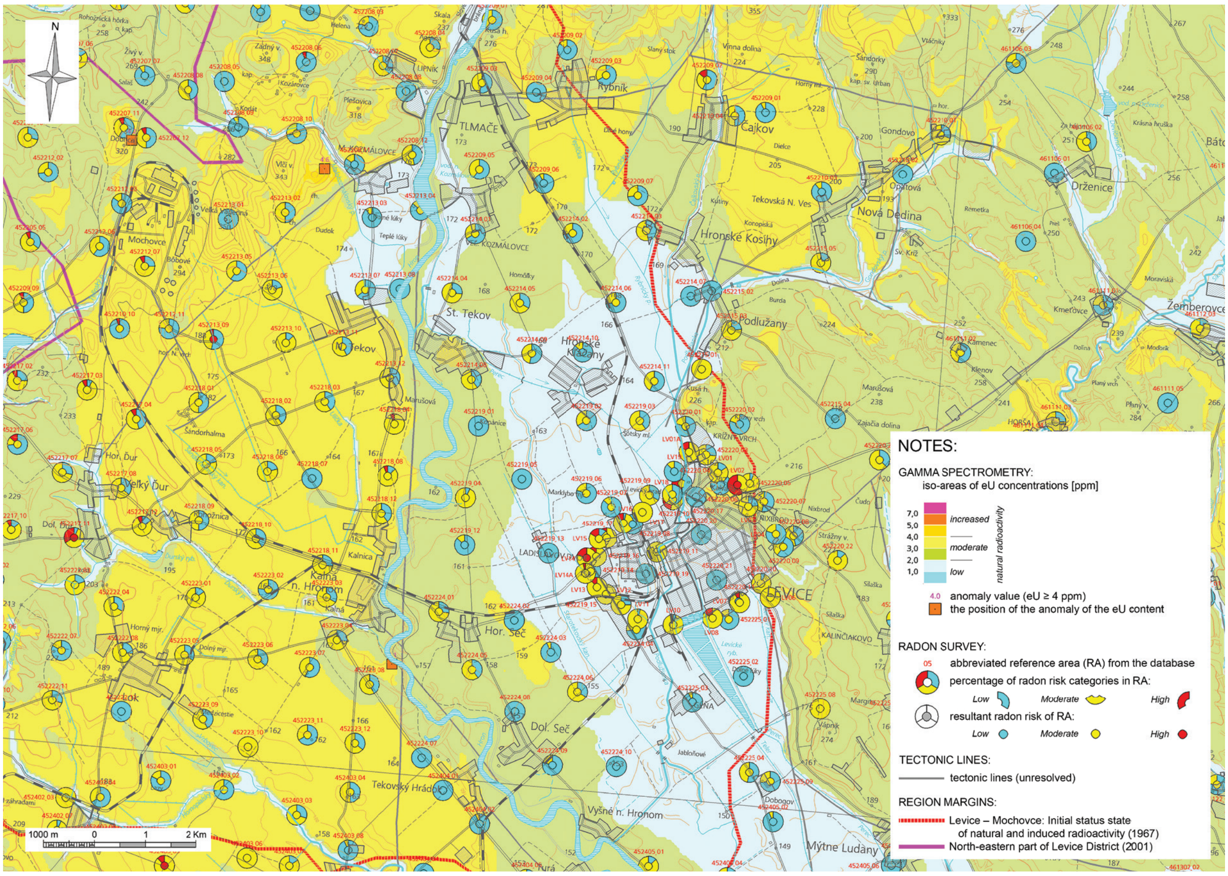


Fig. 2.11 *Summary map of radon risk and concentration projections [ppm], Levice – Mochovce, scale 1 : 50,000 (cut, reduced)*

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.

References:

Bezák, V., Elečko, M., Fordinál, K., Ivanička, J., Kaličiak, M., Konečný, V., Kováčik, M., Maglay, J., Mello, J., Nagy, A., Polák, M., Potfaj, M., Biely, A., Bóna, J., Broska, I., Buček, S., Filo, I., Gazdačko, Ľ., Grecula, P., Gross, P., Havrila, ., Hók, J., Hraško, Ľ., Jacko, S. ml., Jacko, S. st., Janočko, J., Kobulský, J., Kohút, M., Kováčik, M., Lexa, J., Madarás, J., Németh, Z., Olšavský, M., Plašienka, D., Pristaš, J., Rakús, M., Salaj, J., Siman, P., Šimon, L., Teťák, F., Vass, D., Vozár, J., Vozárová, A. & Žec, B., 2008: Prehľadná geologická mapa Slovenskej republiky 1 : 200 000 [*General geological map of the Slovak Republic 1 : 200,000*], Geofond Archive, Bratislava.

Čížek, P., Gluch, A. & Smolárová, H., 2001: Atlas geofyzikálnych máp a profilov [*Atlas of geophysical maps and profiles*], Interim report, Geofond Archive, Bratislava. In Slovak.

Daniel, J., Lučivjanský, L. & Stercz, M.,1997: Geochemický atlas SR – časť rádioaktivita [*Geochemical atlas SR - part Radioactivity*], Interim report, Geofond Archive, Bratislava. In Slovak.

Daniel, J., Stercz, M., Mašlárová, I., Daniel, V., Mašlár, E., Lehotská, E., Danielová, K., Lučivjanský, L., Novotný, L., Donát, A., Čížek, P. & Kandrík, M., 1999: Geologické faktory životného prostredia – prírodná rádioaktivita [Geological factors of the environment - natural radioactivity], Final report, Geofond Archive, Bratislava. In Slovak.

Gluch, A., Smolárová, H. & Čížek, P., 2005: Reambulácia máp rádioaktivity ^{137}Cs územia Slovenska v mierkach 1 : 200 000 a 1 : 500 000 [*Upgrade of radioactivity maps ^{137}Cs in Slovakia at scales 1 : 200,000 and 1 : 500,000*], Final report, Geofond Archive, Bratislava. In Slovak.

Iglárová, Ľ., Klukanová, A., Wagner, P., Hrašna, M., Cipciar, A., Frankovská, J., Mikita, S., Bajtoš, P., Smolárová, H., Gluch, A., Vlčko, J., Bodiš, D., Ondrášik, M., Ondrejka, P., Liščák, P., Pauditš, P., Petro, Ľ., Dananaj, I., Hagara, R., Moczo, P., Labák, P., Kristeková, M., Ferianc, D., Vanko, J., Kováčiková, M., Záhorová, Ľ., Matys, M., Gajdoš, V., Masarovičová, M., Slávik, I., Vybíral, V., Rapant, S., Greif, V., Brček, M., Kordík, J., & Slaninka, I., 2011: Čiastkový monitorovací systém – geologické faktory, správa za obdobie 2002 – 2009 [*Partial monitoring system – geological factors, report for 2002 – 2009*], Interim report, Geofond Archive, Bratislava. In Slovak.

Káčer, Š., Antalík, M., Lexa, J., Zvara, I., Fritzman, R., Vlachovič, J., Bystrická, G., Brodianska, M., Potfaj, M., Madarás, J., Nagy, A., Maglay, J., Ivanička, J., Gross, P., Rakús, M., Vozárová, A., Buček, S., Boorová, D., Šimon, L., Mello, J., Polák, M., Bezák, V., Hók, J., Teťák, F., Konečný, V., Kučera, M., Žec, B., Elečko, M., Hraško, Ľ., Kováčik, M. & Pristaš, J., 2005: Slovenská republika – digitálna geologická mapa v M 1 : 50 000 a 1 : 500 000 [*Slovak Republic – digital geological map at scales 1 : 50,000 and 1 : 500,000*], Final report, Geofond Archive, Bratislava. In Slovak.

Káčer, S., Antalík, M., Bodiš, D., Cibula, R., Gargulák, M., Gluch, A., Hraško, Ľ., Liščák, P., Malík, P., Mižák, J., Pauk, J. (Esprit, s.r.o.), Rapant, S. & Slaninka, I., 2014: Geologický informačný systém GeoIS [*Geological Information System GeoIS*], Final report, Geofond Archive, Bratislava. In Slovak.

Kubeš, P., Bielik, M., Daniel, S., Čížek, P., Fiľo, M., Gluch, A., Grand, T., Hrušecký, I., Kučharič, Ľ., Medo, S., Pašteka, R., Smolárová, H., Šefara, J., Tekula, B., Ujpál, Z., Valušiaková, A., Bezák, V., Dublan, Š., Elečko, M., Határ, J., Hraško, Ľ., Ivanička, J., Janočko, J., Kaličiak, M., Kohút, M., Konečný, V., Mello, J., Polák, M., Potfaj, M., Šimon, L. & Vozár, J., 2001: Atlas geofyzikálnych máp a profilov [*Atlas of geophysical maps and profiles*], Final report, Geofond Archive, Bratislava. In Slovak.

Decree No. 12/2001 of the Ministry of Health of the Slovak Republic on the Requirements for Provision of Radiation Protection.

Directive of the Ministry of Environment of the Slovak Republic No. 1/2000-3 for the compilation and issue of natural and artificial radioactivity maps at a scale of 1 : 50,000.

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.