 doi: 10.1515/geoca-2016-0019

# In-situ ground gamma spectrometry — an effective tool for geological mapping (the Malé Karpaty Mts., Slovakia)

ANDREJ MOJZEŠ[1] and BARBARA PORUBČANOVÁ[2]

[1]Comenius University in Bratislava, Faculty of Natural Sciences, Department of Applied and Environmental Geophysics, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovak Republic; mojzes@fns.uniba.sk
[2]Slovak Academy of Sciences, Earth Science Institute, Dúbravská cesta 9, 840 05 Bratislava, Slovak Republic; geofbapo@savba.sk

*(Manuscript received September 14, 2015; accepted in revised form March 10, 2016)*

**Abstract:** This contribution presents the results of profile in-situ gamma spectrometry measurements that sought to determine the content of natural radionuclides $^{40}$K, $^{238}$U and $^{232}$Th in a near surface horizon of rocks, their weathering cover and soils in the area of the Malé Karpaty Mts. It is widely established that the exploration of radioactivity of bedrocks and cover rocks can be a very effective and useful tool for both geological mapping, for identifying deposits of mineral resources, and even addressing the issues of structural and tectonic geology. This assertion is equally confirmed by the ground gamma spectrometry measurements carried out as part of this case study on larger scales, seeking more detailed geological structure solutions. The results obtained provide a welcome addition to an already existing database, which monitors the content of naturally occurring radionuclides individually for every rock lithotype of the Western Carpathians, by elaborating on the data collected by previous research and by updating this database for any future needs. The presented results confirmed the low to medium radioactivity levels of rocks and soils in the studied area. The highest values were detected in granitoids and metamorfic phyllitic rocks of the Malé Karpaty Mts. core; the lowest values were detected in carbonates, arenaceous sediments and, above all, amphibolite bodies. In this way, the presented results of the interpreted profile (P5) confirm the model of local geological structure as represented on the most up-to-date edition of the geological map of the Malé Karpaty Mts. (Polák et al. 2011).

**Key words:** Western Carpathians, Malé Karpaty Mts., geological mapping, geophysical exploration, in-situ ground gamma spectrometry, concentration of $^{40}$K, $^{238}$U and $^{232}$Th in rock.

## Introduction

Radiometric survey methods used in applied geophysics, which typically include radiometry as well as more sophisticated gamma spectrometry (in all of their airborne, carborne, ground and well log modifications) and soil emanometry, represent the primary techniques of surveying and evaluating the natural radioactive resources and their geological mapping based on nuclear radiation detection. Employing gamma spectrometry for the purposes of geological mapping is made possible by the very existence of measurable differences in contents of natural radionuclides $^{40}$K, $^{238}$U and $^{232}$Th in rocks, their weathering cover and soils. Knowledge of the geochemical and mineralogical structures and processes that determine their distribution and mobility in bedrocks, cover rocks and soils plays a decisive role in interpretation of the results of gamma spectrometry measurements, preferably in combination with information provided by other geophysical survey methods (electrical, magnetic, electromagnetic, seismic, gravimetry), satellite images, geological and soil maps and accurate positional GIS data. As the largest proportion of detected gamma rays originate in the depth horizon of 30 cm at maximum (which comprises the weathering and/or soil cover of bedrock), gamma spectrometry is considered a near surface mapping method. Therefore, it is essential to understand the relationship between the bedrock and its weathering and soil cover, which is influenced by weathering processes themselves, such as disequilibrium of radioactivity in the uranium decay series or the impact of soil moisture and vegetation cover on measured data. The most important factors of successful mapping of lithological units by gammaspectrometry survey are: 1) the contrasts in radioelement content between lithological assemblages, 2) the extent of bedrock exposure and soil cover, 3) the relative distribution of transported and in-situ soils, 4) the nature and type of weathering, 5) the soil moisture content and 6) the vegetation cover (IAEA-TECDOC-1363 2003).

The results of ground profile gamma spectrometry with GPS positional data from stations in the studied area of the Pezinské Malé Karpaty Mts. were processed and analysed with regard to the general geological map of Slovakia on the scale of 1:200,000 (Bezák et al. 2008) and to the last edition of the geological map of the Malé Karpaty Mts. on the scale of 1:50,000 (Polák et al. 2011). The lithological units in question were attributed values of rock radioactivity with the results being contrasted with the findings of previous surveys in the region. Conclusions reached in doing so were used to determine the effectiveness of the applied survey gamma spectrometry method for the purposes of describing the spatial distribution of the individual lithological units and setting up the boundaries between them.

## The study area and its geological structure

The studied area of the Malé Karpaty Mts. lies in the southwestern part of Slovakia, extending more than 100 km from Bratislava to Nové Mesto nad Váhom in the SW–NE direction (Fig. 1) with their largest part — the Pezinské Malé Karpaty Mts. — starting at the Lamač Gate in the SW and ending at Buková Village in the NE (Vass et al. 1988). The Malé Karpaty Mts. form the SW edge of an extensive Carpathian belt of more than 2000 km spreading across Slovakia, West Ukraine and Romania.

The Malé Karpaty Mts. are an integral part of the Western Carpathian orogeny. They represent a horst structure tectonically extensively confined by faults with a SE–NW direction (Császár et al. 2000, 2001; Bezák et al. 2008; Vozár et al. 2014). The studied area of the Pezinské Malé Karpaty Mts. belongs geologically to the Pezinok-Hainburg Zone of the Tatra-Fatra Belt of core mountains of the Western Carpathians (Plašienka et al. 2007 in Kellerová 2011; Vozár et al. 2014). The Pezinok-Hainburg Zone is predominantly formed by the Tatricum Superunit as the NE continuation of the Central Alpine Unit (correlated with the Lower Austro-Alpine units) (Császár et al. 2000; Vozár et al. 2014) and by a large allochthonous unit — the Bratislava Nappe. The Tatricum Superunit comprises two partial subautochthonous units — the Borinka Unit and the Orešany Unit. **The Borinka Unit** (Infratatricum) stretches along the NW slopes and foothill belt of the Pezinské Malé Karpaty Mts. from Lamač and Záhorská Bystrica villages to the NE, but mainly in a wide belt that exists between Borinka and Pernek villages

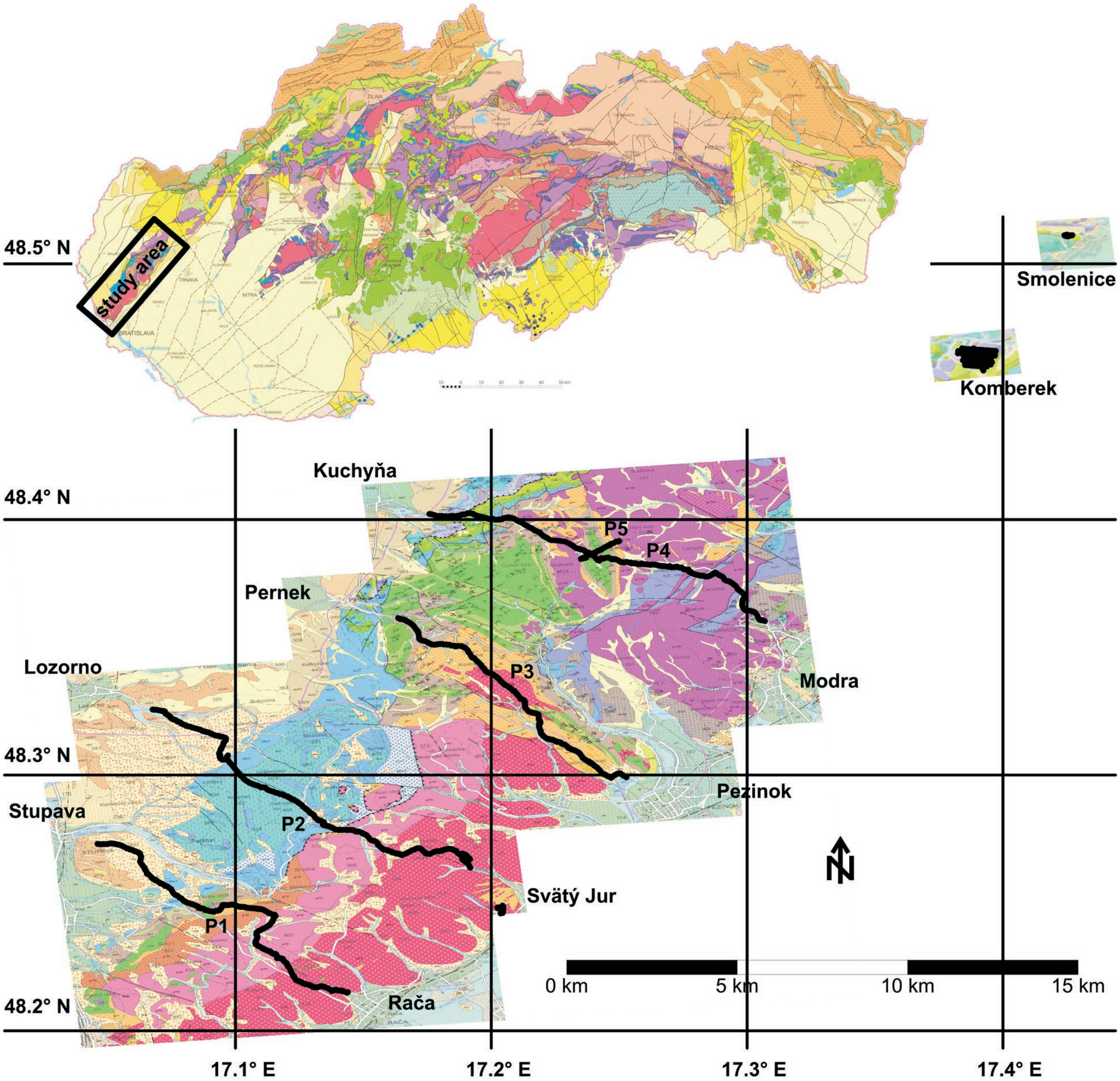


**Fig. 1.** Tectonic sketch of the Western Carpathians (Biely et al. 1996) with the Malé Karpaty Mts. position and the geological map of the study area with localization of profile measurements.

(Fig. 1). The Borinka Succession consists mostly of clastic to coarse-clastic Jurassic sediments that can be divided into five main formations: the Korenec, Marianka, Slepý, Prepadlé and Somár formations. **The Orešany Unit** (Tatricum) represents the NE tip of the Pezinské Malé Karpaty Mts. between Píla–Červený Kameň and the Horné Orešany villages (Fig. 1). Similarly to the Borinka Unit, it is in a subautochthonous position to the Bratislava Nappe, but they differ in filling: in the case of the latter, it consists of complexes of pre-Alpine crystalline basement of the Tatricum and from its Late Permian–Mesozoic sedimentary cover affected by anchizonal metamorphosis. The pre-Alpine basement (the so-called Doľany crystalline basement) is to be found on the SE slopes between Častá and Dolné Orešany villages and it is formed by lithologically monotonous, formerly clayey-sandy Early Palaeozoic sediments changed by Variscan low- to medium-grade metamorphosis to chlorite-biotite phyllites to siliceous and micaceous biotite-garnet gneisses. The cover sequence begins with sparse arkose sandstones of the Late Permian Devín Formation followed by quartzites of the Lúžna Formation and the Middle Triassic Ramsau dolomites of the Werfen Formation followed by the Jurassic–Cretaceous Orešany Succession, which consists of the Slepý, Lučivná, Solírov and Poruba formations. **The Bratislava Nappe** (Tatricum) covers the largest part of the Pezinské Malé Karpaty Mts. (Fig. 1) and is composed of fairly variegated complexes of both the pre-Alpine basement and its Mesozoic sedimentary cover. The Early Palaeozoic crystalline basement consisting of medium- to low-grade metamorphites and bodies of Variscan deep-seated rocks is divided into the Pezinok Unit (Group) formed by a monotonous Silurian–Devonian complex of formerly flysch-sandy and clayey sediments converted to quartzite mica schist gneisses and biotite phyllites, and the Pernek Unit (Group), which represents a Devonian–Lower Carboniferous volcanic-sedimentary succession metamorphosed into green shales facies during the Variscan orogeny. Two large granitoid massifs were placed into the Early Palaeozoic metamorphic mantle during the Variscan orogeny (Fig. 1): the Bratislava and the Modra Massifs. In its southern part, the Bratislava Massif penetrates the rocks of the Pezinok Succession and is made up of leucocratic S-type granites and monzogranites rich in pegmatite and aplite veins. The younger Modra Massif in the northern part of the Pezinské Malé Karpaty Mts. is formed by granodiorites to tonalites that intruded into higher structural levels than those of the Bratislava Massif, principally in the rocks of the Pernek Succession. The Tatric sedimentary cover sequences are preserved in the Bratislava Nappe in several, partly separated places, and differ substantially. Late Palaeozoic sediments in the Pezinské Malé Karpaty Mts. have their origin most likely in the premature local Upper Permian terrestrial clastics of the Devín Formation. Werfenian clastics consist of the sandstone Lúžna Formation and shale Werfenian Formation. The Jurassic–Early Cretaceous sequences appear along the north-western border of the Bratislava fundament in 4 successions: Devín, Kuchyňa, Kadluby and Solírov.

From the overburdens of the Malé Karpaty Mts. horst, mostly the relics of Middle Miocene sediments are preserved on up-lifted edges and piedmonts of the mountains. From the morphological point of view, the Pezinské Malé Karpaty Mts. are low expressive mountains, as is indicated by local types of Quaternary cover sediments: for the most part, they include relatively thick eluvial weathering covers, slope deluvia and alluvial sediments of flood plains. In some places, widespread proluvial fans originated at openings of valleys into the surrounding basins. Finally, a small proportion of eolian loesses and sands are also present in the area (Plašienka et al. 2007 in Kellerová 2011).

## Methods applied and methodology of work

Numerous surveys, aimed at surface mapping of the distribution of individual rock units in various locations, were realized in the area of the Pezinské Malé Karpaty Mts. between 2010 and 2014 (see Fig. 1). These included especially the following four transverse profiles of 2010: Rača–Stupava (profile P1), Svätý Jur–Lozorno (P2), Pezinok–Pernek (P3) and Modra (Harmónia)–Kuchyňa (P4) selected for the purpose of regional geological mapping. In 2011, measurements were carried out along the P5 profile situated between the altitude quotes of Starý kopec (528 m a.s.l.) and Skalnatá (704 m a.s.l.) exploring the presence of amphibolite bodies in the region of Modra-Piesok. A complex geological and geophysical survey was realized in 2012 near Orešany village in the area of the altitude quote of Krč (409 m a.s.l.), located in the karst region Komberek; with the aim of locating and exploring karstic structures — sinkholes, pits and caves (Putiška et al. 2013, 2014). The 2013 geophysical survey near Svätý Jur village sought to locate pegmatite veins in-detail and finally, another detailed geophysical survey of an archaeological site at Molpír in Smolenice village in 2014 attempted to detect archaeological artefacts. The results of the five above-mentioned research projects, which admittedly dealt with a wide range of issues, can be used for evaluation of the mapping potential of the employed in-situ ground gamma spectrometry method.

Nuclear geophysical properties of the rock and soil environment were determined by using the survey method of in-situ ground gamma spectrometry. Measurements were carried out along profiles, with the step of stations ranging from 1 to 50 m depending on the focus of each task. This method allows us to measure three values at each measurement point (station), based on gamma rays detection in the near surface horizon of soil, weathering cover and rock: mass concentrations of $^{40}$K [%K], $^{238}$U [ppm eU] and $^{232}$Th [ppm eTh]. As the determination of $^{238}$U and $^{232}$Th is indirect, by detection of gamma radiation of their daughter products ($^{214}$Bi, resp. $^{208}$Tl), the determined values of $^{238}$U and $^{232}$Th concentrations are valid under condition of radioactive equilibrium in their disintegration series. In addition, the total gamma activity $eU_t$ [Ur] (Ur is the unit of radioelement concentration; 1 Ur~1 ppm eU) was calculated by the equation (Regulation of the Ministry of Environment No. 1/2000-3)

$$eU_t\,[\mathrm{Ur}]=2.79\,K\,[\%]+eU\,[\mathrm{ppm}]+0.48\,eTh\,[\mathrm{ppm}] \quad \text{(Eq. 1)}$$

The field measurements were realized by portable gamma spectrometer GS-256 (manufactured by former state company Geofyzika Brno, Czechoslovakia) with scintillation detector NaI(Tl) 76×76 mm and 256-channel analyser. All measurements were carried out in surface $2\pi$ geometry (not in holes) following the traditional procedure: first, grass, leaves and a thin upper humus layer of soil were removed and the surface was levelled in a 1–1.5 m radius on every measurement point. The duration of measurement was 2 minutes for each point. The points were placed without exception in a natural environment, never in landfills that could form part of fields, forest roads or waste disposal sites. Moreover, the measurements were scheduled in summer and autumn periods with stable, dry weather in order to avoid the results being influenced by changes in soil moisture. Consistency of the data measured by the instrument was regularly checked by repeating the measurements on the same point in the field, as well as in laboratory conditions. The precision and repeatability of instrument readings based on repeated measurements at several stations were evaluated by calculation of the average quadratic error ($\sigma$) and the relative average quadratic error (p) by equations (Čížek et al. 1993)

$$\sigma=\pm[\Sigma(x_i-y_i)^2/2N]^{1/2} \ ; \ p=200N\sigma/[\Sigma(x_i+y_i)] \quad [\%] \quad \text{(Eq. 2)}$$

where N — number of stations with repeated measurements,
x — first measurement,
y — second (repeated) measurement at the same station.

The position of all measurement points was determined using a GPS device in WGS84 coordinates of longitude and latitude.

## Results and discussion

On the whole, the survey in the Pezinské Malé Karpaty Mts. covered 1816 measurement points: 1039 points placed on 4 regional profiles P1–P4 (the length of each was ca. 10 km), 39 points situated on profile P5 in the area of Modra–Piesok (ca. 1.5 km long), 225 points on 9 profiles in the Komberek Karst (the length of which varied from 600 to 1000 m), 324 points on 10 profiles in the region near Svätý Jur village (of length from 15 to 300 m) and 185 points on 3 profiles on the archaeological site Molpír in Smolenice village (each profile was 60 m long).

Results of repeated measurements calculated by Eq. 2 are presented in Table 1.

Using its position established using GPS data, every measurement point was located on the general geological map of Slovakia with the scale 1:200,000 (Bezák et al. 2008) and the measured value of radioactivity in the form of $eU_t$, %K, ppm eU and ppm eTh was then attributed to each of the corresponding geological units. From the point of view of the survey's focus on single localities the simplest situation was those with a detailed survey: on the archaeological site Molpír in Smolenice village where all measurements were done within only one lithological unit — the Cretaceous

**Table 1:** Evaluation of repeated measurements.

| | Total gamma activity $eU_t$ | Potassium $^{40}$K | Uranium $^{238}$U | Thorium $^{232}$Th |
|---|---|---|---|---|
| Average quadratic error $\sigma$ | 0.24 Ur | 0.1 %K | 0.48 ppm eU | 0.79 ppm eTh |
| Relative everage quadratic error p [%] | 1.8 | 4.5 | 18.7 | 11.5 |
| No. of repeated measurements | 57 | | | |

Poruba Formation of marlstones, shales, sandstones, sandy limestones and orthoconglomerates and on the pegmatite site near Svätý Jur village where most of the measurement points lie on granites and granodiorites rich in pegmatites (the Bratislava type) and only a few on Quaternary deluvial and fluvial sediments. The geological structure of the other 3 localities is much more varied and, of course, the most complex is along 4 regional profiles.

The geological units explored (24) and the basic statistical parameters of their radioactivity ($eU_t$, %K, ppm eU and ppm eTh) are presented in Table 2 and in Fig. 2. Table 3 provides an overview of the lithotypes with the highest and the lowest values of radioactivity.

The measurements carried out as a part of this gamma spectrometry survey confirmed that the study area is a region with medium to low rock radioactivity (Matolín 1976; Daniel et al. 1996, 1999). The highest values were shown by igneous rocks, namely medium-grained muscovite granites to granodiorites of the Bratislava Massif (2.6 %K, 3.3 ppm eU, 9.7 ppm eTh and 17.3 Ur), fine-grained biotite granites to granodiorites of the Bratislava Massif (2.6 %K, 2.8 ppm eU, 9.9 ppm eTh and 16.9 Ur) and coarse-grained granites to granodiorites of the Bratislava Massif with pegmatites, while the third group also manifested a lower concentration of thorium (2.2 %K, 3.0 ppm eU, 7.8 ppm eTh and 14.7 Ur). The lowest values of radioactivity of igneous rocks were detected in the case of biotite granodiorites and tonalites of the Modra Massif (1.7 %K, 2.5 ppm eU, 6.3 ppm eTh and 11.4 Ur). In the category of crystalline rocks, very high values of radioactivity were measured in phyllites and phyllitic slates (2.1 %K, 4.3 ppm eU, 7.8 ppm eTh and 15.5 Ur), the radioactivity was lower in the case of gneisses and paragneisses (1.6 %K, 2.7 ppm eU, 6.9 ppm eTh and 11.8 Ur). Schists and meta-quartzites tend to belong among rocks with a higher concentration of uranium and thorium (2.3 %K, 2.7 ppm eU, 7.3 ppm eTh and 14.4 Ur). The lowest radioactivity value in the category of crystalline rocks was detected in fine-grained and medium-grained amphibolite bodies (1.3 %K, 2.1 ppm eU, 4.4 ppm eTh and 8.8 Ur). A common characteristic of Mesozoic rocks is their low radioactivity value. The Jurassic limestones (1.4 %K, 2.3 ppm eU, 5.8 ppm eTh and 9.8 Ur) tend to have lower values than the Triassic ones (1.9 %K, 2.8 ppm eU, 8.9 ppm eTh and 13.5 Ur) (Kellerová 2011). The values characteristic for the Neogene sandstones, conglomerates and gravels are very low (1.6 %K, 2 ppm eU, 5.4 ppm eTh and 10.5 Ur) (Kellerová 2011) except for the Jakubov Formation (2.4 %K, 2.5 ppm eU, 7.8 ppm eTh and 14.8 Ur). Finally, the Quaternary deluvial sediments manifest lower values (1.7 %K, 2.4 ppm eU, 5.9 ppm eTh

**Table 2:** Basic statistical parameters of radioactivity of the studied geological units.

| Lithotype map index | No. of stations | Radioactivity variables | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total gamma activity $eU_t$ [Ur] | | | | | Potassium $^{40}K$ [%K] | | | | | Uranium $^{238}U$ [ppm eU] | | | | | Thorium $^{232}Th$ [ppm eTh] | | | | |
| | | Mi | Ma | ø | Me | σ | Mi | Ma | ø | Me | σ | Mi | Ma | ø | Me | σ | Mi | Ma | ø | Me | σ |
| kr147 | 138 | 7.6 | 19.2 | 11.8 | 11.3 | 2.3 | 0.9 | 3.2 | 1.6 | 1.5 | 0.5 | 1.6 | 5.1 | 2.7 | 2.7 | 0.7 | 3.1 | 10.8 | 6.9 | 6.8 | 1.5 |
| kr162 | 26 | 2.9 | 14.4 | 8.8 | 10.6 | 4.2 | 0.4 | 2.7 | 1.3 | 1.3 | 0.7 | 0.5 | 8.5 | 2.1 | 1.9 | 1.5 | 0.4 | 8.8 | 4.4 | 5.0 | 2.3 |
| kr17 | 16 | 11.7 | 21.0 | 16.9 | 17.6 | 2.4 | 1.4 | 3.7 | 2.6 | 2.6 | 0.6 | 1.8 | 3.4 | 2.8 | 2.7 | 0.5 | 7.7 | 12.3 | 9.9 | 9.9 | 1.5 |
| kr26 | 73 | 9.2 | 22.1 | 17.3 | 17.5 | 2.7 | 1.3 | 4.3 | 2.6 | 2.6 | 0.5 | 1.7 | 5.9 | 3.3 | 3.1 | 0.8 | 1.5 | 15.2 | 9.7 | 9.8 | 2.5 |
| kr35 | 457 | 7.5 | 22.7 | 14.7 | 14.3 | 2.1 | 0.7 | 4.4 | 2.2 | 2.1 | 0.5 | 1.6 | 6.2 | 3.0 | 2.9 | 0.6 | 2.2 | 13.6 | 7.8 | 7.9 | 1.8 |
| kr50 | 36 | 4.8 | 18.2 | 11.4 | 12.1 | 3.0 | 0.6 | 2.7 | 1.7 | 1.8 | 0.5 | 1.1 | 4.3 | 2.5 | 2.4 | 0.7 | 2.1 | 9.9 | 6.3 | 6.2 | 1.8 |
| kr94 | 15 | 8.6 | 20.5 | 15.5 | 15.0 | 3.6 | 0.9 | 3.1 | 2.1 | 2.1 | 0.8 | 2.0 | 8.4 | 4.3 | 4.0 | 2.0 | 3.0 | 13.9 | 7.8 | 8.3 | 3.5 |
| kr97 | 16 | 12.3 | 20.0 | 14.4 | 13.7 | 1.9 | 1.8 | 3.6 | 2.3 | 2.2 | 0.4 | 1.7 | 3.5 | 2.7 | 2.6 | 0.5 | 4.7 | 9.3 | 7.3 | 7.2 | 1.3 |
| mj13 | 8 | 9.1 | 14.6 | 11.7 | 12.1 | 2.1 | 0.9 | 1.6 | 1.3 | 1.3 | 0.3 | 1.4 | 3.2 | 2.5 | 2.6 | 0.6 | 7.4 | 12.1 | 9.4 | 9.5 | 1.5 |
| mj25 | 6 | 11.0 | 13.8 | 12.7 | 13.1 | 1.2 | 1.3 | 1.9 | 1.7 | 1.8 | 0.2 | 2.3 | 3.7 | 2.8 | 2.7 | 0.5 | 6.9 | 8.6 | 7.7 | 7.7 | 0.7 |
| mj26 | 32 | 8.9 | 14.6 | 11.2 | 11.1 | 1.3 | 1.1 | 2.5 | 1.5 | 1.4 | 0.3 | 1.2 | 3.7 | 2.4 | 2.3 | 0.5 | 5.1 | 9.7 | 7.4 | 7.4 | 1.2 |
| mj29 | 3 | 12.8 | 14.5 | 13.6 | 13.4 | 0.9 | 1.6 | 2.2 | 1.9 | 1.9 | 0.3 | 2.7 | 3.0 | 2.8 | 2.8 | 0.1 | 7.6 | 9.2 | 8.5 | 8.6 | 0.8 |
| mj61 | 2 | 14.2 | 16.9 | 15.5 | 15.5 | 1.8 | 2.2 | 2.5 | 2.3 | 2.3 | 0.3 | 3.2 | 3.4 | 3.3 | 3.3 | 0.2 | 8.3 | 10.3 | 9.3 | 9.3 | 1.4 |
| mk38 | 201 | 3.8 | 15.8 | 7.0 | 6.5 | 2.5 | 0.5 | 2.4 | 0.9 | 0.9 | 0.4 | 0.3 | 3.5 | 1.3 | 1.2 | 0.6 | 2.5 | 11.4 | 5.3 | 5.0 | 1.6 |
| mt16 | 108 | 5.1 | 20.0 | 12.5 | 13.0 | 3.2 | 0.6 | 3.5 | 1.5 | 1.5 | 0.5 | 0.9 | 4.3 | 3.0 | 3.0 | 0.7 | 2.8 | 13.5 | 8.8 | 9.5 | 2.5 |
| mt22 | 43 | 4.1 | 15.0 | 12.1 | 12.9 | 2.7 | 0.5 | 2.0 | 1.4 | 1.4 | 0.3 | 1.4 | 4.5 | 3.1 | 3.2 | 0.8 | 1.7 | 12.3 | 8.5 | 9.3 | 2.3 |
| mt3 | 7 | 8.9 | 17.1 | 12.0 | 11.4 | 2.8 | 1.3 | 3.0 | 1.9 | 1.7 | 0.6 | 1.4 | 2.5 | 1.9 | 1.9 | 0.4 | 4.5 | 10.6 | 6.6 | 5.9 | 2.1 |
| mt61 | 15 | 9.2 | 15.1 | 13.2 | 13.8 | 1.7 | 0.9 | 2.2 | 1.7 | 1.8 | 0.4 | 1.7 | 3.9 | 3.0 | 3.0 | 0.6 | 5.2 | 10.6 | 8.5 | 8.6 | 1.7 |
| ng12 | 19 | 10.7 | 23.0 | 14.8 | 14.8 | 3.2 | 1.7 | 4.1 | 2.4 | 2.4 | 0.6 | 1.6 | 3.5 | 2.5 | 2.3 | 0.5 | 4.5 | 11.0 | 7.8 | 8.2 | 1.9 |
| q19 | 13 | 7.0 | 11.3 | 9.4 | 9.0 | 1.4 | 1.2 | 2.0 | 1.6 | 1.6 | 0.2 | 1.0 | 2.7 | 1.7 | 1.8 | 0.6 | 2.4 | 7.0 | 4.5 | 4.3 | 1.4 |
| q20 | 222 | 5.7 | 22.7 | 14.6 | 14.3 | 2.7 | 0.8 | 4.3 | 2.2 | 2.2 | 0.5 | 1.0 | 4.8 | 2.6 | 2.6 | 0.7 | 1.9 | 17.3 | 8.2 | 8.0 | 2.3 |
| q24 | 87 | 5.3 | 23.9 | 11.2 | 10.8 | 3.1 | 0.8 | 3.5 | 1.7 | 1.6 | 0.5 | 1.1 | 6.5 | 2.4 | 2.3 | 0.9 | 2.2 | 14.9 | 5.9 | 5.7 | 2.0 |
| q7 | 240 | 4.2 | 19.0 | 11.5 | 11.1 | 2.8 | 0.6 | 3.3 | 1.6 | 1.5 | 0.5 | 0.9 | 5.3 | 2.6 | 2.5 | 0.7 | 2.6 | 13.7 | 6.4 | 6.2 | 1.9 |
| rauhwackes | 33 | 6.5 | 15.2 | 11.5 | 12.4 | 2.5 | 0.5 | 2.1 | 1.4 | 1.4 | 0.4 | 1.5 | 4.9 | 2.9 | 2.8 | 0.8 | 3.3 | 11.4 | 7.9 | 8.6 | 2.4 |

Explanations (legend by Bezák et al., 2008, 2009):

Mi – minimum

Ma – maximum

Me – median

ø – arithmetic mean (AVG)

σ – standard deviation (SD)

kr147 – metamorphic rocks with medium to higher metamorphic grade: biotitic paragneisses with flaky graphite

kr162 – metamorphic rocks with high metamorphic grade: fine- to medium-grained amphibolites (the Pezinok Succession)

kr17 – leucocratic and vein types of granitoides: leucocratic fine-grained biotite and two-mica granites to granodiorites

kr26 – granites to granitoides: medium-grained leucocratic muscovite and two-mica granites, granodiorites (the Bratislava type)

kr35 – granites to granitoides: coarse-grained muscovite, muscovite-biotite granites, granodiorites enriched in pegmatites (the Bratislava type)

kr50 – granodiorites to tonalites: biotite granodiorites to tonalites (the Modra type)

kr94 – metamorphic rocks with lower metamorphic grade: graphite-sericite phyllites, graphite metasandstones

kr97 – metamorphic rocks with lower metamorphic grade: phyllites, micaceous shales, metapelites of biotite-garnet zone

mj13 – the Jaseniny Formation: light-grey, pink, low-marly thin bedded to slab-like limestones

mj25 – the Prepadlé Formation: grey, massive or thick bedded, textureles fine-grained limestones with lithoclasts of the Triassic carbonates, bioclastic limestones, sandstones

mj26 – the Korenec Formation: dark-grey sandy claystones, sandstones with beds of sandy limestones

mj29 – the Somár Formation: polymict, non-stratificated breccia

mj61 – the Trlenská dolina Formation: light-grey to pink, sandy-crinoidal limestones

mk38 – the Poruba Formation: marlstones, clayey-sandy shales, sandstones, sandy limestones, ortoconglomerates

mt16 – the Gutenstein limestones: dark-grey and black, thick bedded, stratified, vermiform limestones

mt22 – the Ramsau dolomites: grey stratified dolomites

mt3 – the Lúžna Formation: light-grey, pink, red quartzites, quartz sandstones, arkose sandstones, conglomerates

mt61 – the Carpathian Keuper: quartz sandstones, arkose, conglomerates, clayey shales, dolomites

ng12 – the Jakubov Formation: the Devínska Nová Ves Formation: conglomerates, sands

q19 – deluvial-polygenetic sediments: loamy-clayey and sandy slope loams

q20 – deluvial sediments: mostly loamy-rocky (less sandy-rocky) slope sediments and debris

q24 – deluvial sediments in all: litofacially unsorted slope sediments and debris

q7 – fluvial sediments: lithofacially unsorted plain loams or sandy to gravelly loams of valley alluvial plains and plains of ravine streams

rauhwackes – tectonically derived from the Gutenstein limestones (Putiška et al., 2014)Mi – minimum

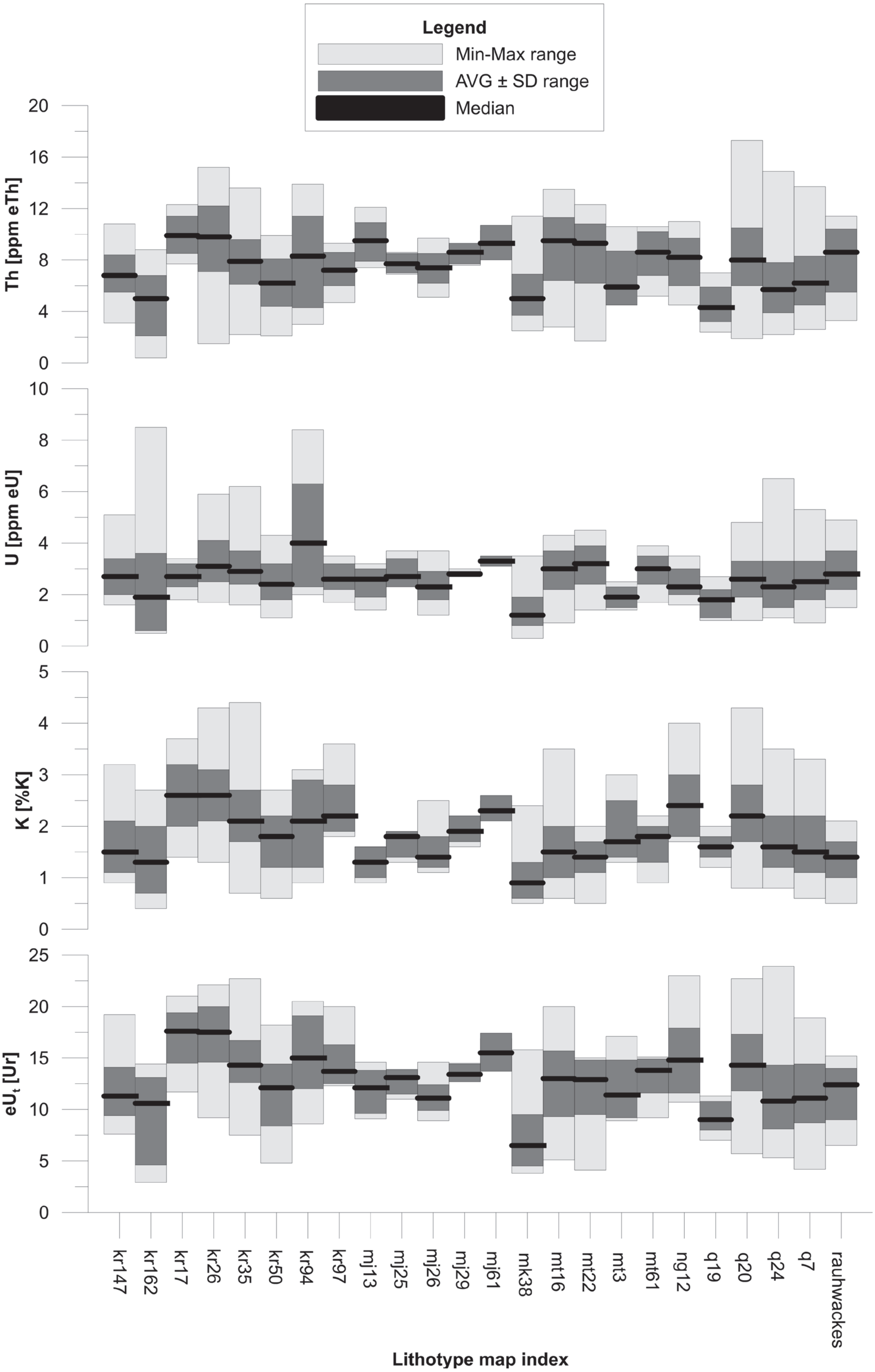


**Fig. 2:** Selected statistical parameters of the studied lithological units (range, AVG±SD, median).

**Table 3:** Lithotypes with the highest and the lowest values of radioactivity (based on AVG).

| Sequence No. | Sequence of rocks by average (AVG) value of single radioactivity variable: | | | |
|---|---|---|---|---|
| | by total gamma activity $eU_t$ [Ur] | by potassium $^{40}K$ content [%K] | by uranium $^{238}U$ content [ppm eU] | by thorium $^{232}Th$ content [ppm eTh] |
| 1. | kr26 (17.3) | kr26 (2.6) | kr94 (4.3) | kr17 (9.9) |
| 2. | kr17 (16.9) | kr17 (2.6) | mj61 (3.3) | kr26 (9.7) |
| 3. | mj61 (15.5) | ng12 (2.4) | kr26 (3.3) | mj13 (9.4) |
| 4. | kr94 (15.5) | mj61 (2.3) | mt22 (3.1) | mj61 (9.3) |
| 5. | ng12 (14.8) | kr97 (2.3) | kr35 (3.0) | mt16 (8.8) |
| 6. | kr35 (14.7) | q20 (2.2) | mt61 (3.0) | mt22 (8.5) |
| 7. | q20 (14.6) | kr35 (2.2) | mt16 (3.0) | mt61 (8.5) |
| 8. | kr97 (14.4) | kr94 (2.1) | rauhwackes (2.9) | mj29 (8.5) |
| 9. | mj29 (13.6) | mt3 (1.9) | mj25 (2.8) | q20 (8.4) |
| 10. | mt61 (13.2) | mj29 (1.9) | mj29 (2.8) | rauhwackes (7.9) |
| 11. | mj25 (12.7) | q24 (1.7) | kr17 (2.8) | kr94 (7.8) |
| 12. | mt16 (12.5) | mt61 (1.7) | kr97 (2.7) | ng12 (7.8) |
| 13. | mt22 (12.1) | kr50 (1.7) | kr147 (2.7) | kr35 (7.8) |
| 14. | mt3 (12.0) | mj25 (1.7) | q20 (2.6) | mj25 (7.7) |
| 15. | kr147 (11.8) | q7 (1.6) | q7 (2.6) | mj26 (7.4) |
| 16. | mj13 (11.7) | kr147 (1.6) | kr50 (2.5) | kr97 (7.3) |
| 17. | rauhwackes (11.5) | q19 (1.6) | mj13 (2.5) | kr147 (6.9) |
| 18. | q7 (11.5) | mt16 (1.5) | ng12 (2.5) | mt3 (6.6) |
| 19. | kr50 (11.4) | mj26 (1.5) | q24 (2.4) | q7 (6.4) |
| 20. | q24 (11.2) | mt22 (1.4) | mj26 (2.4) | kr50 (6.3) |
| 21. | mj26 (11.2) | rauhwackes (1.4) | kr162 (2.1) | q24 (5.9) |
| 22. | q19 (9.4) | kr162 (1.3) | mt3 (1.9) | mk38 (5.3) |
| 23. | kr162 (8.8) | mj13 (1.3) | q19 (1.7) | q19 (4.5) |
| 24. | mk38 (7.0) | mk38 (0.9) | mk38 (1.3) | kr162 (4.4) |

Explanations:

kr26 (17.3) – lithotype map index of rock and the value of radiaoctivity in brackets

List of lithotype map indexes as in Tab. 2 explanations

AVG – arithmetic mean

and 11.2 Ur) when compared with fluvial sediments (1.6 %K, 2.6 ppm eU, 6.4 ppm eTh and 11.5 Ur).

The presented results clearly show that the lithological unit with the highest total gamma activity is represented by the medium-grained granitoids of the Bratislava type (kr26). These are closely followed by fine-grained biotite granitoids (kr17), low-grade metamorphosed graphite-sericite phyllites (kr94), the Neogene Jakubov Formation (ng12) and coarse-grained granitoids with pegmatites (the Bratislava type) (kr35). The other extremity of the spectrum is constituted by rocks with the lowest total values of gamma activity in the studied area, namely the flysh Poruba Formation (mk38) followed by high-grade metamorphosed amphibolites (kr162) and Quaternary deluvial loamy-clayey and sandy slope loams (q19/q24) (Table 3).

The data obtained corresponds relatively well with the results of previous measurements that provided an outline of the radioactive character of the rocks in this area. It should be pointed out, however, that the data collected in previous surveys are less detailed (Daniel et al. 1996, 1999) but also confirm the low radioactivity values of rocks of the Malé Karpaty Mts.

An example of the possible uses of in-situ ground gamma spectrometry for purposes of rock mapping in geology is illustrated using the results of measurements carried out on the P5 profile (Fig. 1). Figure 3 shows the geological structure of the P5 profile area in more detail on the general geological map of Slovakia with the scale 1:200,000 (Bezák et al. 2008) and Figure 4 shows the same on the newest edition of the geological map of the Malé Karpaty Mts. with the scale 1:50,000 (Polák et al. 2011). Figure 5 presents the course of the total gamma activity $eU_t$ values along the P5 profile.

Cross section 1 under the $eU_t$ curve on Fig. 5 documents the boundaries of geological lithotypes as observed on the geological map by Bezák et al. (2008) (Fig. 3). Cross section 2 on Fig. 5 represents the boundaries of geological lithotypes as observed on the geological map by Polák et al. (2011) (Fig. 4). Cross section 3 on Fig. 5 represents an interpretation of these boundaries based on measured data and the values of total gamma activity $eU_t$. It appears relatively simple to identify certain lithotypes bearing in mind $eU_t$ values characteristic of them: this is the case of amphibolites (kr162/193a), associated with the minimum values on the $eU_t$ curve; granodiorites and tonalites (kr50/188), graphite-sericite phyllites (kr94/196b) and biotite paragneisses (kr147/199a) that typically demonstrate slightly elevated values of $eU_t$ grouping close to the typical averages (Tables 2 and 3). To some extent, it is also possible to determine the location of both fluvial and deluvial Quaternary (q/20).

Certain segments of the $eU_t$ curve (Fig. 5) are characterized by a greater scatter of values and can therefore point to zones of transition where individual lithotypes overlap. This is illustrated primarily by the segment A, which represents a transition zone between granodiorites (kr50) and biotite paragneisses (kr147) by Bezák et al. (2008) or a transition zone between gneisses (199a) and phyllites (196b) by Polák et al. (2011), and the segment E pointing to a transition zone between amphibolites (kr162) and graphite-sericite phyllites (kr94) by Bezák et al. (2008) or a transition zone from amphibolites (193a) through phyllites (196b) and gneisses (199a) to granodiorites (188) by Polák et al. (2011). Since its $eU_t$ values are higher when compared with the kr162/193a segments, the B segment (stations of 680, 720 and 760 m) could indicate the presence of material of the black schists body with ore mineralization (191) mixed into an environment consisting primarily of amphibolite bodies (see Fig. 4 by Polák et al. 2011). The whole wide section between 540 and 1380 m might be interpreted as an extensive amphibolite body, which is intersected approximately at the 1100 m point, situated in a geomorphological depression, by a tectonic zone oriented in a northwest-southeast direction. The weathering processes that take place in the amphibolite body disrupted by the tectonic zone result in elevated values of $eU_t$ in segments D and C while these are contrasted with low values of $eU_t$ in peripheral pluton zones, which form the geomorphological elevations, where amphibolite material remains intact. The $eU_t$ curve further shows that the granodiorite body (kr50) documented on the geological map of Bezák et al. (2008) in Fig. 3 in section 900–1060 m (cross-section 1 in Fig. 5) is absent from the interpreted cross-section 3 or might not be crossed by the P5 profile (Fig. 5). On the other hand, the increased value of $eU_t$ at the 1080 m station (Fig. 5) could be the result of granodiorite material from the nearby granodiorite body (188) (Fig. 4, by Polák et al. 2011).

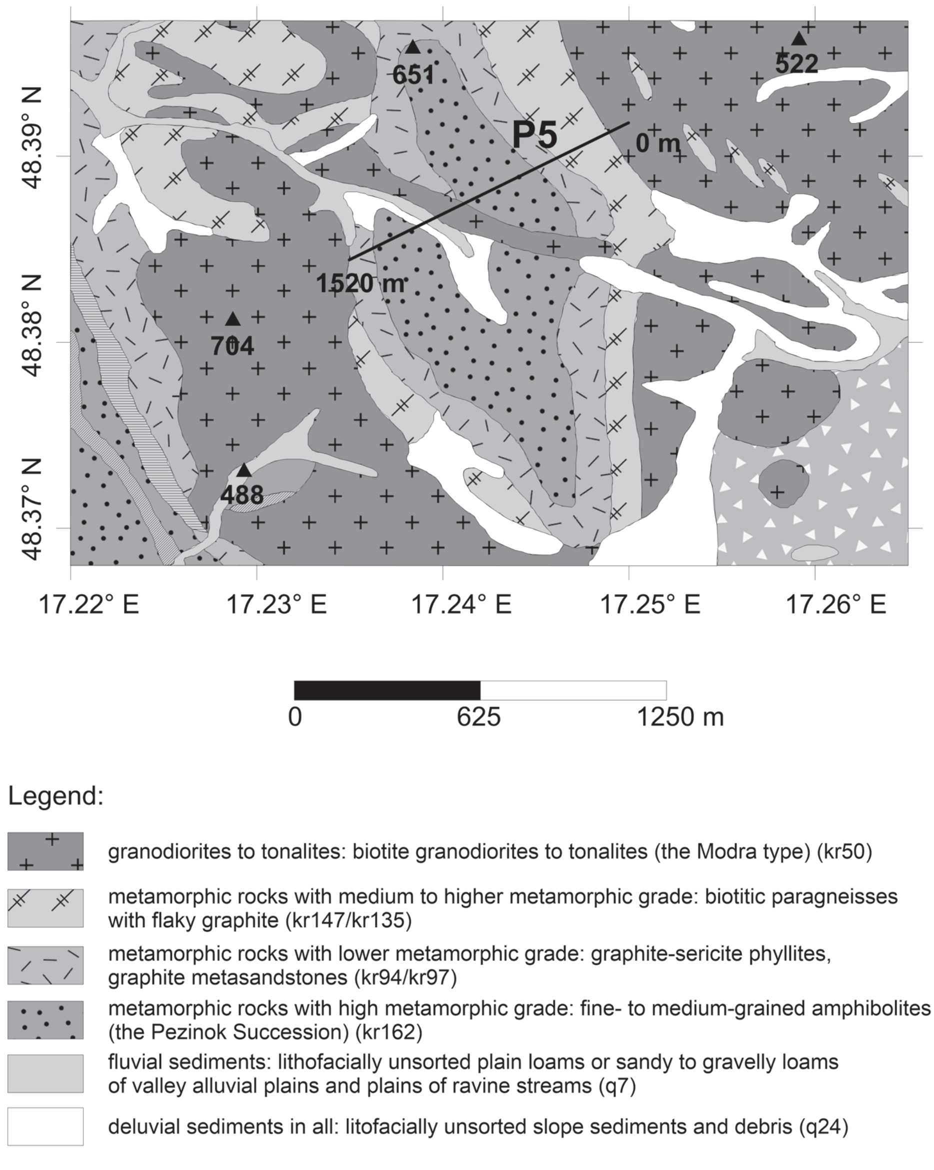


**Fig. 3.** Section of geological map of the studied area by Bezák et al. (2008) with localization of the P5 profile.

In this sense, it is possible to conclude that the results of the gamma spectrometry measurements carried out on the P5 profile correspond better with the data on the new edition of the geological map of the Malé Karpaty Mts. in Fig. 4 (Polák et al. 2011) than with the older edition of the map in Fig. 3 (Bezák et al. 2008).

## Conclusions

The profile in-situ gamma spectrometry measurements of the content of natural radionuclides $^{40}K$, $^{238}U$ and $^{232}Th$ in rocks and their weathering and soil cover in the Malé Karpaty Mts., which were the subject of the present geophysical survey, confirmed their effective application in dealing with issues that arise in geological mapping of distribution of rock lithotypes. Interpretation of the results of such measurements combined with a detailed analysis and revision of field and meteorological conditions during measurement as well as a thorough knowledge of the geological principles that govern rock distribution, their weathering processes and geomorphological conditions, can significantly contribute to defining geological boundaries and providing more accurate characterization of already identified rock lithotypes and any changes in their properties.

In conformity with previous research, the measurements confirmed the low and medium level of rock radioactivity in the studied area. The highest values of radioactivity characterized the granites, granodiorites and metamorphosed phyllites. The lowest values were measured in Jurassic limestones, arenaceous sediments and mainly amphibolites. The interpreted results along the profile P5 correspond to

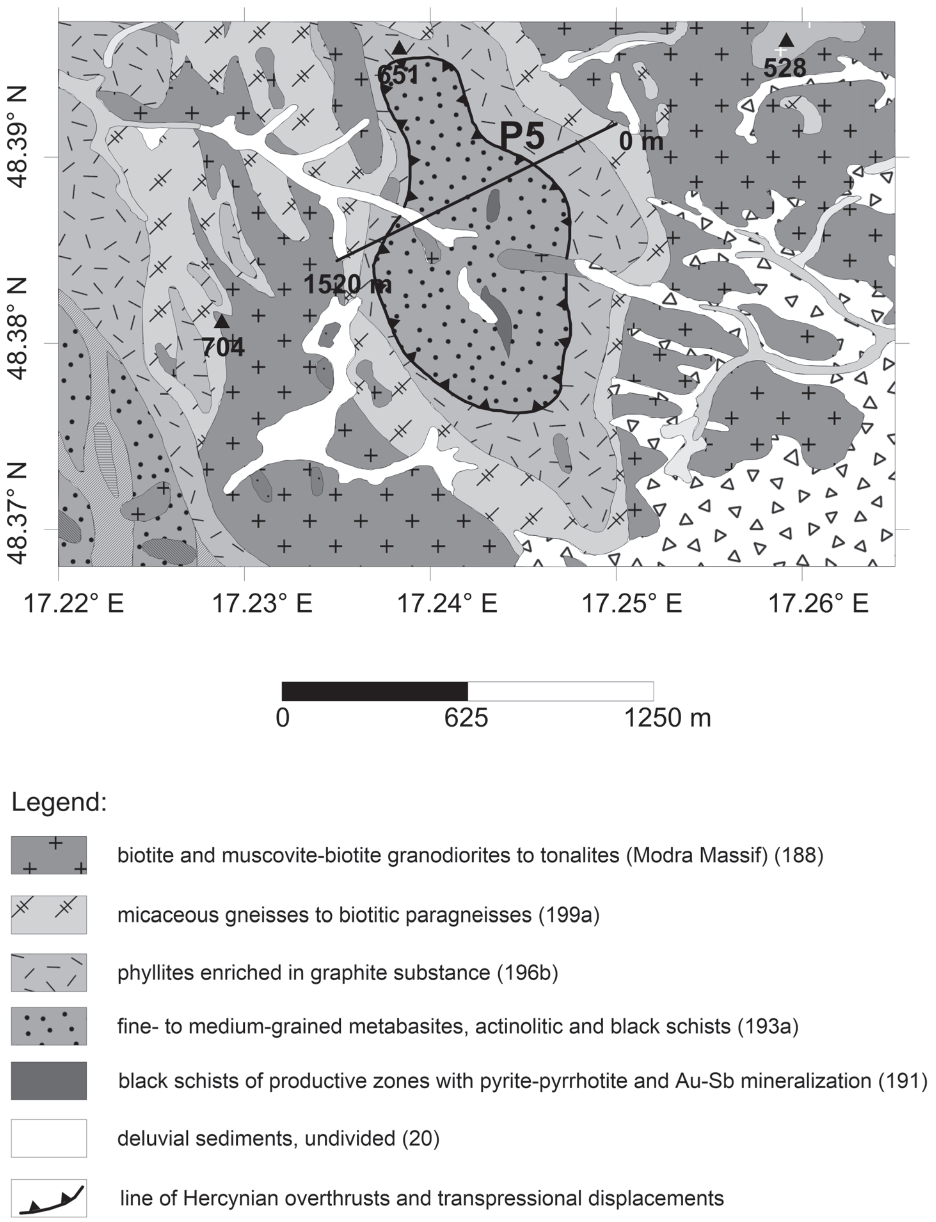


**Fig. 4.** Section of geological map of the studied area by Polák et al. (2011) with localization of the P5 profile.

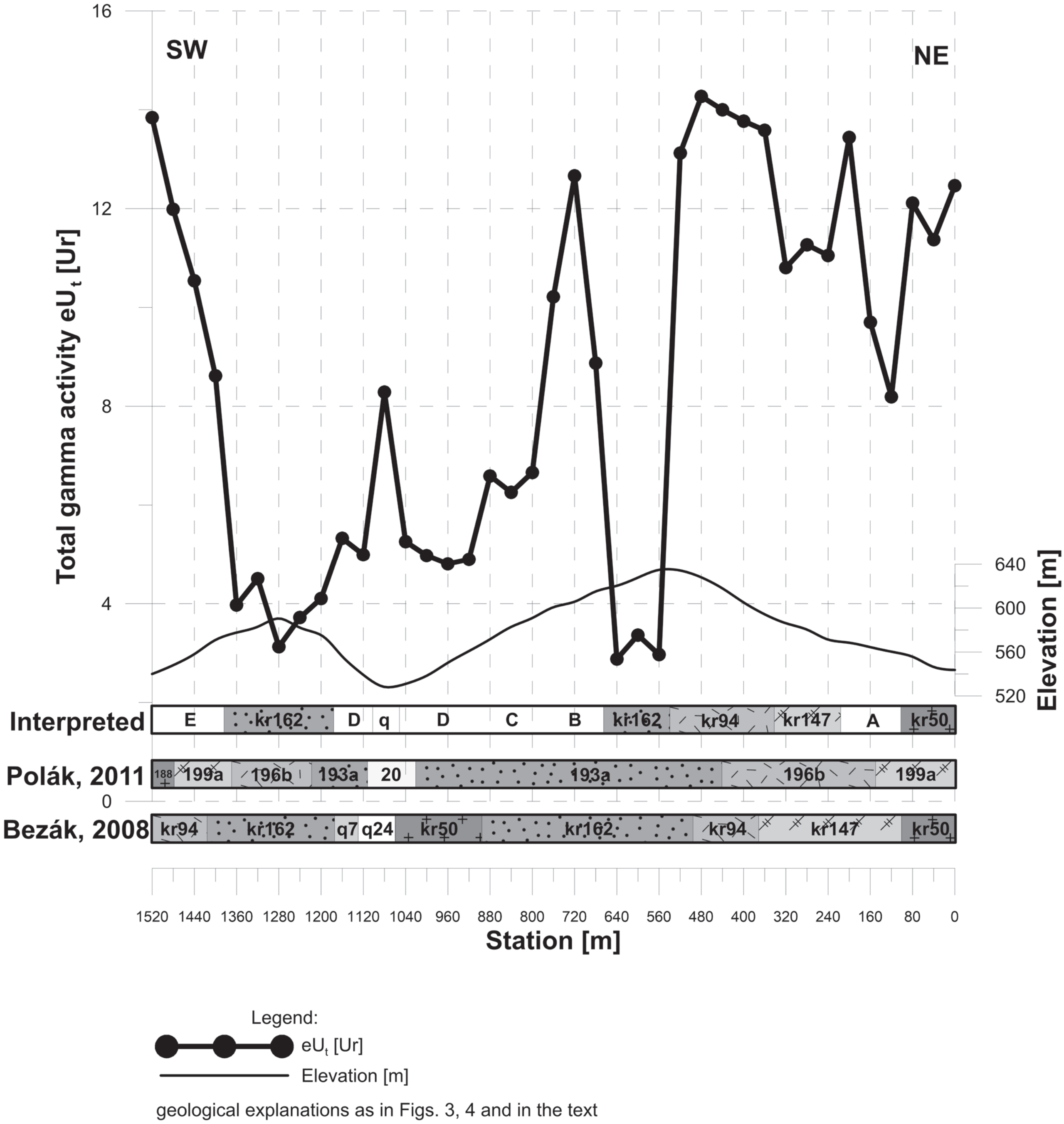


**Fig. 5.** Curve of total gamma activity $eU_t$ along the P5 profile with map and interpreted cross sections.

information about the local geological structure presented on the up-to-date geological map by Polák et al. (2011).

The fact that the results obtained represent yet another valuable contribution to the overall database of rock radioactivity and thus permits us to increase its statistical reliability so that it can continue to provide a solid base with which all new measurements can be contrasted appears to be no less important. Both the measurements and the interpretation of results confirm that an active cooperation between experts in exploration geophysics and other disciplines concerned with geological mapping is both inevitable and desirable considering its indisputable effectiveness.

**Acknowledgements:** This contribution is the result of implementation of the projects: APVV-0194-10, APVV-0099-11, APVV-0129-12, VEGA 1/0131/14, VEGA 1/0141/15 and VEGA 1/0462/16. The authors are thankful to the Slovak Research and Development Agency for support.

## References


Bezák V. (Ed.), Elečko M., Fordinál K., Ivanička J., Kaličiak M., Konečný V., Kováčik M. (Košice), 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 M., Hók J., Hraško Ľ., Jacko S., ml., Jacko S., st., Janočko J., Kobulský J., Kohút M., Kováčik M. (Bratislava), Lexa J., Madarás J., Németh Z., Olšavský M., Plašienka D., Pristáš J., Rakús M., Salaj J., Siman P., Šimon L., Teťák F., Vass D., Vozár J., Vozárová A. & Žec B. 2008: General geological map of the Slovak Republic 1: 200 000. *MŽP SR–ŠGÚDŠ*, Bratislava. ISBN 978-80-89343-21-8

Bezák V. (Ed.), Biely A., Broska I., Bóna J., Buček S., Elečko M., Filo I., Fordinál K., Gazdačko Ľ., Grecula P., Hraško Ľ., Ivanička J., Jacko S. Sr., Jacko S. Jr., Janočko J., Kaličiak M., Kobulský J., Kohút M., Konečný V., Kováčik M. (Bratislava), Kováčik M. (Košice), Lexa J., Madarás J., Maglay J., Mello J., Nagy A., Németh Z., Olšavský M., Plašienka D., Polák M., Potfaj M., Pristáš J., Siman P., Šimon L., Teťák F., Vozárová A., Vozár J. & Žec B. 2009: Explanations to the general geological map of the Slovak Republic 1:200 000. *ŠGÚDŠ*, Bratislava, 1–534. ISBN 978-80-89343-28-7 (in Slovak with English summary).

Biely A. (comp.), Bezák V. (ed.), Elečko M., Kaličiak M., Konečný V., Lexa J., Mello J., Nemčok J., Potfaj M., Rakús M., Vass D., Vozár J. & Vozárová A. 1996: Geological Map of Slovakia 1:500,000. *MŽP SR – ŠGÚDŠ*, Bratislava.

Császár G. (Ed.) 2000: Danube region environmental geology programme DANREG explanatory notes. *Jb. Geol. Bundesanst.* 142/4, Wien, 1–607.

Császár G. (Ed.), Pistotnik J., Scharek P., Kaiser M., Darida-Tichy M., Nagy E., Pristaš J., Horniš J., Halouzka R., Elečko M., Konečný V., Lexa J., Nagy A., Vass D. & Vozár J. 2001: Surface geological map of Danube region (DANREG), 1:100,000. *MŽP SR–Geocomplex, a.s.–ŠGÚDŠ*, Bratislava.

Čížek P., Brozman F., Gluch A. & Smolárová H. 1993: Geological factors of environment — natural radioactivity. *Partial report. Ministry of Environment*, Bratislava, 1–90 (in Slovak).

Daniel J., Lučivjanský L. & Stercz M. 1996: Geochemical atlas of Slovakia, part IV – Natural rock radioactivity. *Ministry of Environment*, Bratislava, 1–88.

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: Geological factors of environment – natural radioactivity. *Final report. Ministry of Environment*, Bratislava, 1–198 (in Slovak).

IAEA-TECDOC-1363 2003: Guidelines for radioelement mapping using gamma ray spectrometry data. *International Atomic Energy Agency*, Vienna, 1–173.

Kellerová S. 2011: Profile gamma spectrometry in the Malé Karpaty Mts. — measurement and data processing. *Diploma Thesis work. Dptm. of Applied and Environmental Geophysics, Faculty of Natural Sciences, Comenius University in Bratislava*, Bratislava, 1–72 (in Slovak).

Matolín M. 1976: Radioactivity of rocks of the Western Carpathians. *Charles University*, Prague, 1–127 (in Czech).

Polák M., Plašienka D., Kohút M., Putiš M., Bezák V., Filo I., Olšavský M., Havrila M., Buček S., Maglay J., Elečko M., Fordinál K., Nagy A., Hraško Ľ., Németh Z., Ivanička J. & Broska I. 2011: Geological map of the Malé Karpaty Mts. Region, 1:50 000. *Ministry of Environment, State Geological Institute of Dionýz Štúr*, Bratislava.

Putiška R., Kušnirák D., Dostál I., Pašteka R. & Mojzeš A. 2013: Investigation in sinkhole terrains using complex of geophysical methods — case study in the karst area, Slovakia. In: Near Surface Geoscience 2013. *NSGD*, Houten, 1–5 (electronic).

Putiška R., Kušnirák D., Dostál I., Lačný A., Mojzeš A., Hók J., Pašteka R., Krajňák M. & Bošanský M. 2014: Integrated geophysical and geological investigations of karst structures in Komberek, Slovakia. *J. Cave Karst Stud.* 76, 3, 155–163.

Regulation of the Ministry of Environment of the Slovak Republic No. 1/2000-3 for compilation and edition of maps of natural and artificial radioactivity in scale 1:50 000 (in Slovak).

Vass D., Began A., Gross P., Kahan Š., Köhler E., Lexa J. & Nemčok J. 1988: Regional geological classification of the Western Carpathians and northern projections of the Pannonian Basin to the territory of ČSSR, 1:500 000. *SGÚ – GÚDŠ – GEOFOND*, Bratislava (in Slovak).

Vozár J. (Ed.), Ebner F., Vozárová A., Haas J., Kovács S., Sudar M., Bielik M. & Péró Cs. 2014: Variscan and Alpine terranes of the Circum-Pannonian region. *Slovak Academy of Sciences – Comenius University*, Bratislava, 1–244. ISBN 978-80-971609-9-9