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Correlation of time-different ground radiometry datasets on an example of fault survey (Hradište border fault, Turiec Basin, Western Carpathians, Slovakia)

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Abstract: Complex geophysical survey (seismic tomography, electrical resistivity tomography and electromagnetic interference measurement, spontaneous potential, ground penetration radar, gravimetry, magnetometry and radiometry) was carried out along 450 m-long profile crossing the assumed map track line of the Hradište border fault to specify its position and some of its features. As a result, a 115 m-wide fault zone was identified, vertically or steeply dipped to the south-east and east. Because of incompatibilities between the results of deep-range geophysical methods (seismics, geo-electrics, gravimetry and magnetometry) and the results of shallow-range radiometric methods (ground gamma-ray spectrometry and soil radon emanometry), the latter were measured twice, in 2012 and 2016 years. The comparison of results of both radiometric measurements shows an acceptable level of linear correlation mainly for thorium concentration (R = 0.87), gamma dose rate (R = 0.84), radon activity concentration (R = 0.69) and potassium concentration (R = 0.66), but very low one for uranium concentration (R = 0.12). Alongside, no correlation between soil uranium concentration and activity concentration of radon in soil air was determined. These results confirm the behaviour of measured radiometric quantities in soils and weathered rock covers, and strong influenceability mainly of uranium and radon presence in shallow subsurface horizon by changing meteorological conditions.

Key words: fault, ground gamma-ray spectrometry, soil radon emanometry, weather conditions, repeatability, correlation

1. Introduction

All shallow geophysical in situ exploration techniques are overwhelmed by time changing weather conditions. But while the damp or wet ground subsurface is an advantage for conductive geo-electric techniques, the same one counts, e.g. for much lower radioactivity signal from deeper soil and rock

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horizons for ground gamma-ray spectrometric technique. That's why the main effort is to carry out the survey during the period with stable appropriate weather conditions. This could be an issue mainly during the long-lasting surveys as the correction of influenced radiometric measured data is not simple. The point of such strong dependence of soil and rock radioactivity on weather changes is that in situ radiometry methods are dealing with unstable natural chemical radioelements, some of which are relatively reactive (potassium, uranium) and therefore movable in the environment, and radon, even though inert, is gas also capable of longer movement.

Main reasons causing the variations of gamma activity of rocks and soils are (i) changes of rock and soil moisture, (ii) changes of atmospheric pressure and (iii) changes of air temperature and wind speed (*Filimonov, 1975*). They can cause the changes of gamma activity signal up to 12%, 5% and 5%, respectively (*Filimonov, 1975*). Another contribution is represented by atmospheric radon (exhalation of soil radon into atmosphere) causing the change of gamma activity in uranium window of about 25% (*Filimonov, 1975*). Atmospheric radon trapped in temperature inversion layers close to the ground can strongly affect results of airborne gamma-ray spectrometry (uranium) measurements (*IAEA, 2003*). This effect can be registered to a lesser extent also in ground gamma-ray spectrometry measurements very close to ground surface (*Prutkina and Šaškin, 1984; Mojzeš, 1998, 2009*). Precipitation can have a large effect on uranium estimation due to wash radon daughter products attached to dust particles in the atmosphere down to the ground with rain (more than 2000% in uranium ground concentrations after *Charbonneau and Darnley (1970)* or 170% after *Filimonov (1975)*). Gamma-ray surveying should therefore not be carried out during rainfall or shortly thereafter. Soil radon concentrations in a year cycle are also influenced by weather conditions.

Many works have been dedicated to monitor and analyse the time dependence of the radon activity concentration (RAC) of radon gas in soil air on meteorological parameters (temperature, humidity and pressure) to understand and more precisely specify the radon risk from geological basement (*Matolín and Prokop, 1992; Holý et al., 1997; Cigolini et al., 2009; Mojzeš and Putiška, 2012; Moreno et al., 2016; Petersell et al., 2017; Miklyaev et al., 2021*). A specific factor that reduces assay precision is also the statistical nature of radioactivity.

2. Subject and area of study

Main target of study was to carry out, process and evaluate the results of two time-different profile measurements at the same area by two in situ radiometric methods: ground gamma-ray spectrometry and soil radon emanometry. The goal was not to perform any monitor measurements in a particular period, just to carry out two single measurements in different times and compare the results. A 450 m-long line was selected for this purpose. The first measurement was performed on May 31, 2012, and the second one from April 19 to 21, 2016, both trying to do under the similar appropriate weather conditions and at the same stations along the profile with 5 – 20 m step of measurement. These measurements were a part of complex geophysical measurements carried out for the purposes to characterize the position and some parameters of the Hradište border fault representing the tectonic contact between the Lúčanská Malá Fatra Mts. and the Turiec Basin (Western Carpathians, Slovakia) in the vicinity of the Bystrička Village close to the town of Martin (*Kušnirák et al., 2020*) (Figs. 1 and 2).

The two tectonic units are composed of completely different rocks. The Lúčanská Malá Fatra Mts. is composed of the Tatric crystalline complex, while the Turiec Basin is filled with Neogene sediments. As the composition of these units is completely different it can be assumed that they are also characterized by different physical properties including the radioactivity of present rocks and soils. The 450 m-long profile A–A′ extends almost perpendicular to the Hradište fault (Fig. 2), which separates these two tectonic units.

3. Methods

Radiometric methods are sometimes very useful for detailed study of a fault and its geological surroundings. Mainly soil radon (^{222}Rn) emanometry may give valuable information about gas permeability of faulted rocks and, together with gamma-ray spectrometry, it can help to find boundaries between different lithological units. ^{222}Rn being a gaseous element, soil radon emanometry is an atmo-geochemical survey method based on measuring alpha activity in soil air samples from different depths of rock, weathering cover and soil. This activity results from alpha disintegration processes in the nuclei of radon isotope ^{222}Rn and its daughter products. Its parent ra-

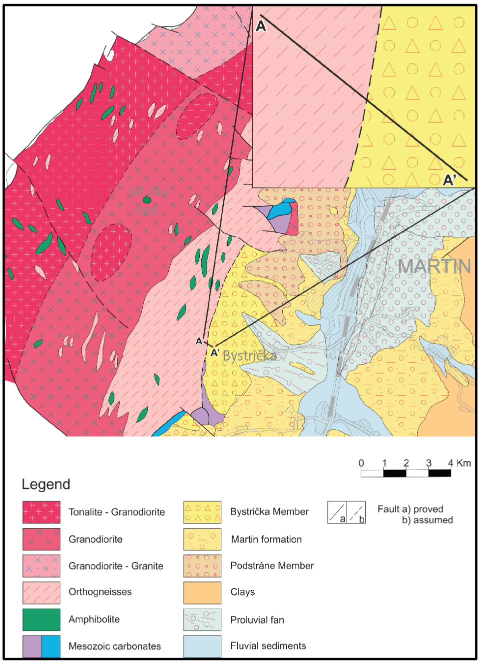

Fig. 1. Simplified geological map of the Turiec Basin and its surroundings. The study area is highlighted by the red rectangle (after *Kováč et al., 2011* and *Bielik et al., 2013*).

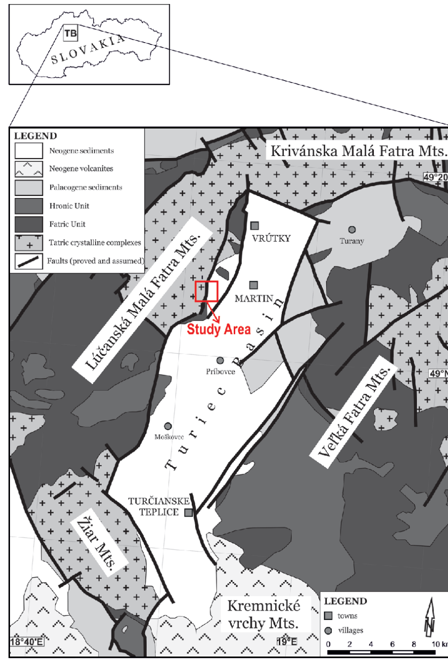

Fig. 2. Location of the investigated Profile A–A′ on a detailed geological map (after *Polák et al., 2008*). Coordinates of the first and final points of the profile are A: 49°03′27.7″N; 18°50′46.57″E and A′: 49°03′19.91″N; 18°51′4.12″E.

dium isotope ^{226}Ra commonly occurs in basement rocks. A fault system is a very appropriate structure for upward movement of radon and other gases emanating from the interior of the Earth. Therefore, the radon activity concentration (RAC) of the radon gas in the soil air along the profile crossing the assumed fault zone, measured in kBq·m^{-3}, may contribute to its positioning. Radon measurements were performed on samples from approximately 0.8 m depth by a portable radon detector LUK-3R (producer SMM, Czech Republic). In total, 32 stations in the first field campaign (2012) and 89 stations in the second one (2016), were measured along the same profile with a 5 to 20 m step between stations. A profile survey using ground gamma-ray spectrometry was used to study the radioactivity of rocks, soils and covers. This method allowed us to determine four measures of gamma-ray activity of near-surface rock and soil horizon at each measured station: total gamma-ray activity eUt [ur] (ur is a unit of radioelement concentration, 1 ur ≈ 1 ppm eU), concentration of ^{40}K [% K], concentration of ^{238}U [ppm eU], and concentration of ^{232}Th [ppm eTh], where the letter "e" represents "equivalent". The depth range is relatively shallow, no more than 1 m below the surface, but the method gives useful information mainly for spatial distribution of radioactive elements contained in geological units. In situ measurements were carried out using a portable 256-channel gamma-ray spectrometer GS-256 (producer Geofyzika, Czechoslovakia) with $3'' \times 3''$ NaI (Tl) scintillation detector using a traditional ground survey procedure: grass, old leaves, and the thin uppermost humus soil layer were removed, and ground surface was levelled in a circular area of 1 to 1.5 m in diameter at each measured station. Time of measurement was 2 minutes per station.

In total, 45 stations in the first field campaign (2012) and 90 stations in the second one (2016), were measured along the profile with a 5 and 10 m step between stations. The total gamma-ray activity eU_t reported in old, already unused "ur" units, was converted to present quantity of absorbed dose rate $\dot{D}_a$ in nGy·h^{-1} using the expressions: 1 ur ∼ 1 ppm U ∼ 0.6 μR·h^{-1} (*IAEA, 1976*) and 1 μR·h^{-1} = 2.4139 pGy·s^{-1} (*IAEA, 1990*). For a more objective interpretation, laboratory analysis of soil grain size was performed to evaluate the fraction of fine-grained clay particles in a sample. Eight soil samples were taken from depths down to 1 meter along the measured line. Soil permeability categories were determined based on the ratio between grain diameters below and above 0.063 mm, using the Slovak Technical Norm STN 72 1001 (*STN, 2010*) (Soil and rock classification).

4. Results and discussion

The detailed results of complex geophysical survey (seismic tomography, electrical resistivity tomography and electromagnetic interference measurement, spontaneous potential, ground penetration radar, gravimetry, magnetometry and radiometry) along 450 m-long profile crossing the assumed map track line of the Hradište border fault (Figs. 1 and 2) were published in *Kušnirák et al. (2020)*. Herein we concentrate primarily on results of two radiometric methods (ground gamma-ray spectrometry and soil radon emanometry) that were measured twice along the same line at different time periods (the first one on May 31, 2012, and the second one from April 19 to 21, 2016) and compare such, relatively long-time lapsed results. The measured results are presented in Fig. 3.

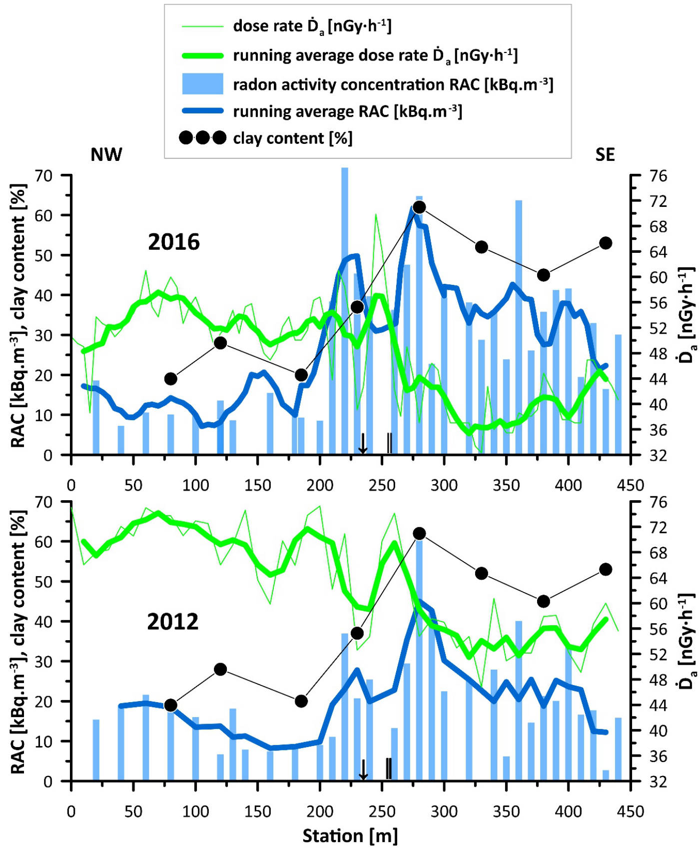

Fig. 3. The results of ground gamma-ray spectrometry and soil radon emanometry measured along the same line in 2012 and 2016 years (explanations: ↓ – map fault position, ‖ – concrete road position).

Short geological interpretation: The 450 m-long NW–SE profile A–A′ (Fig. 2) was designed to cut the map track line of the Hradište border fault approximately at the station of 236 m (Fig. 3). The topographic view of profile (Fig. 4) shows that the terrain creates the lowest depression along the profile at station of around 250 m. At the station of 255 m the profile crosses the concrete field road (between 250 to 260 m) as well. These facts offer a primary idea that the real position of crossing fault line should be somewhere around the depression of 250 m. Most of applied deep-range geophysical methods (seismics, geo-electrics, gravimetry, magnetometry) identified reliably the fault line as a clear boundary contact between subsurface rocks of different physical properties at the station around 165 m, e.g. 85 m north-westwardly from the depression, in the slope of Tatric crystalline rocks (an example is the seismic tomography cross-section in Fig. 4).

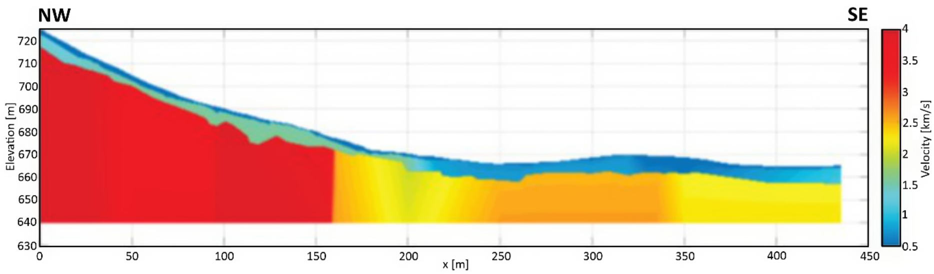

Fig. 4. P-wave velocity cross-section along the Profile A–A′ constructed from seismic tomography measurement. A clear boundary is visible at approximately 165 m from the origin of profile representing the Hradište fault. Tatric crystalline rocks with higher P-wave velocities (>3.5 km·s^{-1}) to the NW of the fault are separated from the SE block with lower velocities (2.0 – 2.5 km·s^{-1}) corresponding to the Neogene sediments (*Kušnirák et al., 2020*).

It is evident that the fault plane is vertical or steeply dipped to SE or E (*Kušnirák et al., 2020*). On the contrary, the results of radiometric methods (Fig. 3) do not show high compatibility with mentioned geophysical methods. Shallow-range ground gamma-ray spectrometry ($\dot{D}_a$) rather shows distribution of two different lithological environments along the profile with the boundary around 210 – 230 m: higher radioactivity of the Tatric crystalline rocks and their weathered cover in the NW part and lower radioactivity of Neogene sediments of the Bystrička Member in the SE part with no indication of fault line at station of 165 m. Soil radon emanometry shows similar results with opposite distribution of values: the lower values of ^{222}Rn activity concentration in soil air (RAC) are tied up to crystalline rocks in the NW part and the higher values in the SE part with Neogene sediments. It follows that soil radon measurements with high probability also map lithology distribution what could also be confirmed by the lower soil clay content in the NW part and the higher one in the SE part (see black line in Fig. 3) of the profile. The highest soil radon activity concentrations at around 280 m together with the highest clay content could indicate the place of upward way out of radon gas from depth of the SE dipping fault plane and this place is the mentioned topographic depression as well. Another, less probable explanation also could be that the lowest values of soil radon activity concentration at around 150 − 160 m really indicate the fault line with such strongly weathered and loosed rock material that radon gas is mostly aired out.

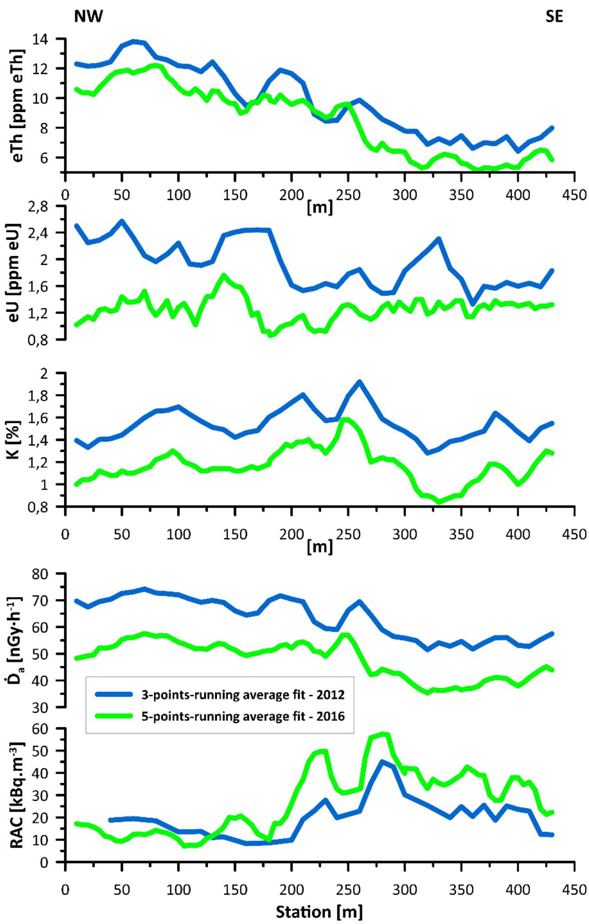

Fig. 5. The courses of repeated radiometric quantities measured in years 2012 and 2016 along the same profile.

These incompatibilities of radiometric results with the results of other geophysical methods were the reason for repeating the measurements once again in 2016 year. The results for each measured radiometric parameter (activity concentration of ^{222}Rn in soil air – RAC, gamma dose rate $\dot{D}_a$, concentration of ^{40}K, concentration of equivalent ^{238}U and concentration of equivalent ^{232}Th) are presented in Fig. 5.

Generally, the 2012 values of each gamma spectrometric quantity are slightly higher than the 2016 ones (Fig. 5). On the other side, the values of activity concentration of radon in soil air act reversely – the 2016 values are higher. The differences are not significantly large (Table 1), and one of the most probable reasons is the soil moisture that seems to be higher in 2016. The running average fits of single radiometric measures show really very good visual sameness between the original (2012) and repeated (2016) measurements (Fig. 5), especially in the case of the gamma dose rate, potassium concentration, soil radon activity concentration and thorium concentration. Less visible is the correlation between uranium concentrations. The visual comparison is also confirmed by linear correlation (Fig. 6) and all results are summed in Table 1. In this way, the correlations slacken from thorium data (R = 0.87) through gamma dose rate (R = 0.84), soil radon (R = 0.69) and potassium (R = 0.66) down to uranium data (R = 0.12).

Table 1. Basic statistical parameters of five radiometric measures in 2012 and 2016 years and their linear correlation (R) 2012 versus 2016.

	2012					2016				
	$\dot{D}_a$ [nGy/h]	K [%K]	U [ppm eU]	Th [ppm eTh]	RAC [kBq.m^{-3}]	$\dot{D}_a$ [nGy/h]	K [%K]	U [ppm eU]	Th [ppm eTh]	RAC [kBq.m^{-3}]
N	45	45	45	45	32	90	90	90	90	89
MIN	46.8	1.2	0.6	5.1	2.9	32.3	0.7	0.2	4.0	4.2
MAX	75.3	2.0	2.8	14.7	63.1	69.9	1.9	2.4	13.0	84.9
AVG	63.5	1.5	2.0	9.8	20.6	47.7	1.2	1.2	8.5	26.9
SD	8.7	0.2	0.5	2.6	12.6	8.0	0.2	0.4	2.6	17.8
R	0.84	0.66	0.12	0.87	0.69	0.84	0.66	0.12	0.87	0.69

Special attention is dedicated to the correlation between the uranium concentration in soil and the activity concentration of radon in soil air as ^{222}Rn is the daughter product of ^{238}U disintegration. Does any relation exist

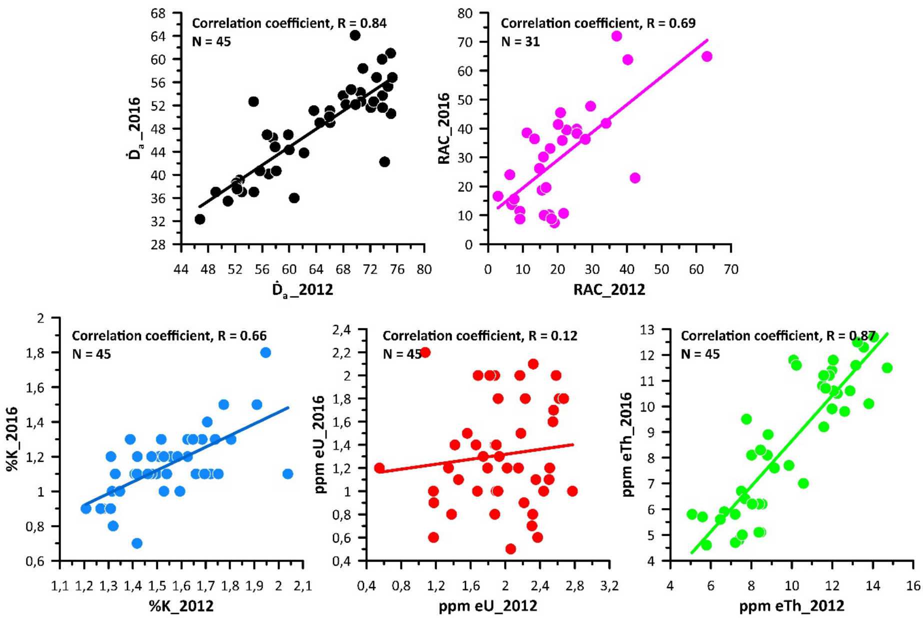

Fig. 6. Linear correlation (R) of single radiometric measures 2012 versus 2016 years.

in our measured data? Figure 7 shows no correlation. This is a common result valid for soils and weathered rock covers (*Mojzeš, 2002*) which simply confirms that the use of uranium concentration data obtained by surface gamma-ray spectrometry survey is unequivocally not applicable for radon risk derivation in this case of strongly weathered geological environment.

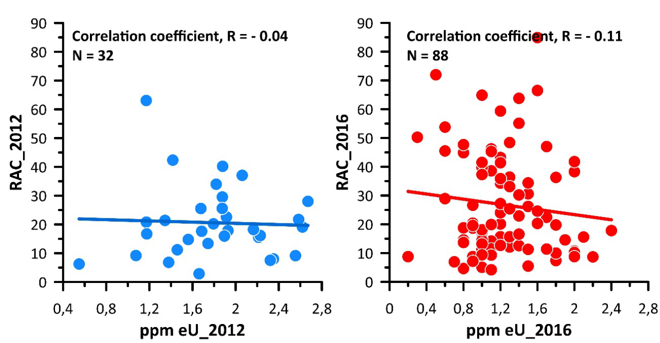

Fig. 7. Linear correlation (R) between uranium and radon in soil in 2012 and 2016 years.

5. Conclusions

From the geological point of view the complex of applied geophysical methods brought valuable information about the character of the studied Hradište border fault. While all deep-ranged geophysical techniques (seismics, geoelectrics, gravimetry, magnetometry) identified coincidently the fault line as a physical boundary vertically or steeply dipped to SE or E at the station around 165 m (*Kušnirák et al., 2020* and Fig. 4), both shallow radiometric techniques (gamma-ray spectrometry and soil radon emanometry) rather identified the lithologic boundary between the Tatric crystalline rocks and the Neogene Bystrička Member sediments at the stations around 210 – 230 m what is closer to the map fault position at the station around 236 m and to the geomorphological display of fault in the form of terrain depression at the stations 250 – 260 m. Herein, the gravitational shift of slope material downward to the depression, plays also an important role. Finally, the highest value of soil radon activity concentration at the station around 280 m could indicate the upward flux of gaseous components from dipped fault line (Fig. 3). In this way, there exists the wide fault zone of around 115 m width between stations from 165 m to 280 m.

Despite a four-years-delay between the first (2012) and repeated (2016) measurement, the courses of selected radiometric measures show very good visual sameness (Figs. 3 and 5) except of uranium concentration. The detailed correlation of all measures between the 2012 and 2016 years presented in Fig. 6 and Table 1 shows the highest linear correlation for thorium concentration ($R = 0.87$), then for gamma dose rate ($R = 0.84$), radon activity concentration ($R = 0.69$), potassium concentration ($R = 0.66$) and the lowest one for uranium concentration ($R = 0.12$). Very low uranium correlation could be attributed to spectral specification of uranium gamma-ray spectra (wide, not very expressive energy peak at 1.76 MeV) and to its relatively high chemical activity and therefore easy movement in shallow near-surface horizon (down to 0.15 – 0.20 m). On the other hand, the activity concentration of radon in deeper horizon of 0.80 m shows higher stability and therefore relatively high correlation. Very high thorium correlation is typical because of thorium high chemical stability.

No correlation between uranium concentration in soil and activity concentration of radon in soil air (^{222}Rn is the ^{238}U decay daughter) is not surprising in such weathered soil and cover environment (Fig. 7). Partly it is caused by different depths of measurement (0.15 – 0.20 m versus 0.80 m) and by relatively high mobility of both ^{238}U and ^{222}Rn radioisotopes. The changing soil wetness also plays an important role as an attenuator of gamma-ray signal coming to detector.

Generally, the additional uncertainties could be assigned to inaccurate localization of stations and different weather conditions between 2012 and 2016 years. The human activity intervention (e.g. landfill) was not observed.

Anyway, the results of repeated radiometric measurements confirm an acceptable level of repeatability of most radiometric measures with uranium exception. This is important mainly in long time lasting survey measurements with the exclusion of periods of severe weather conditions.

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