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Indoor radon monitoring in Zázrivá

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Abstract: Indoor radon survey in Zázrivá was conducted within the framework of the project "Multidisciplinary research of geophysical and structural parameters, and environmental impacts of faults of the Western Carpathians". Monitoring was carried out in selected houses and kindergarten using RamaRn detectors. Annual average of indoor radon varied between 45 and 260 Bq/m^3, with median of 90 Bq/m^3. Seasonal variation with minimum in summer was observed in the majority of monitored rooms. Radon concentration higher than 200 Bq/m^3 was measured only in rooms with direct contact with the subsoil. A possible relation between the position of a monitored building close to an assumed fault line and elevated indoor radon levels was not proven.

Key words: radon, activity concentration, house, kindergarten, integral monitoring, fault

1. Introduction

Radon (^{222}Rn) is naturally occurring noble gas with half-life of 3.82 days. It is produced by an alpha decay of radium (^{226}Ra) in uranium (^{238}U) decay series. Radon is classified as a class I carcinogen, and it is the second leading cause of lung cancer after tobacco smoking, and the most common cause of lung cancer in non-smokers (*Zeeb and Shannoun, 2009*).

Soil gas infiltration is considered as the major source of residential radon. Other sources, such as building materials and water extracted from wells, are less important (*Zeeb and Shannoun, 2009*).

A large number of studies proved an elevated soil radon activity concentration (RAC) in the proximity of active faults (*Font et al., 2008; Neri et al., 2011; Bonforte et al., 2013; Moreno et al., 2018*). The presence of faults nearby buildings may increase indoor RAC (*Drolet and Martel, 2016; Neri et al., 2019*). However, not all surveys confirmed an elevated indoor radon in homes situated close to fault line (*Font et al., 2008; Mojzeš at al., 2017*),

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as its concentration in a house depends also on building characteristics, such as type of foundation, existence of basement, ventilation regime, age of the building and thermal retrofit (*Borgoni et al., 2014; Collignan et al., 2016; Pampuri et al., 2018*).

In Slovakia, the first indoor radon monitoring was performed in randomly selected dwellings during the nineties, using the integral method (*Vičanová, 2003*). In 2005 radon research in houses situated on the fault zone was carried out, together with soil radon measurements, in the Malá Magura Mts. (Horná Nitra region of Central Slovakia). However, the influence of the fault presence on radon concentration was not proven (*Mojzeš at al., 2017*). Indoor radon monitoring was performed within the frame of the Visegrad countries project and the common questionnaire and common measurement protocol was elaborated for (*Müllerová et al., 2016*).

In the recent years indoor radon survey in Slovakia was conducted within the scope of the project "Multidisciplinary research of geophysical and structural parameters, and environmental impacts of faults of the Western Carpathians", which focused on investigation of physical and structural parameters of several representative faults in Slovakia. Radon surveys to verify if the houses built close to the fault zones are prone to high indoor radon were performed at three localities Sološnica, Vydrník and Zázrivá. The preliminary results obtained during the summer monitoring period from all three localities (*Smetanová et al., 2019*) and results obtained from Vydrník (*Smetanová et al., 2022*) were already published. Significantly elevated indoor RAC in one of the monitored houses in Vydrník could be attributed to the Vikartovce fault, or its intersection with crosscutting fault branch.

This paper summarizes the results covering a one year period of indoor RAC monitoring in Zázrivá. The spatial and temporal variations of indoor RAC are evaluated and potential influencing factors are assessed.

2. Methods and monitoring site description

Zázrivá village ($49^\circ\,16'45''$ N, $19^\circ\,09'30''$ E) is situated across the tectonic contact zone of the Pieniny klippen belt unit with both Outer and Inner Western Carpathians units (*Marko et al., 2005*).

Indoor radon survey covered the period from June 2018 to May 2019. Throughout the whole year sets of detectors were changed after three months of exposure (summer period June–August 2018, autumn period September–November 2018, winter period December 2018–February 2019 and spring period March–May 2019). The selection of the survey participants was carried out in accordance with the local authorities, on a voluntary basis. The monitoring was carried out in 44 rooms of 22 houses and in two classrooms in the kindergarten (Figs. 1, 2). Only permanently inhabited houses were included in the survey.

One part of the monitored buildings (Nos. 1–9) was situated close to the southern tectonic contact of the Pieniny klippen belt zone with peri-Klippen Paleogene sediments, in the medium radon risk area – in the central part of Zázrivá. Another part of the detectors was placed in the buildings at the vicinity of a supposed map trace of the neotectonically active E–W Kozinec fault inside the Pieniny klippen belt zone, in a high radon risk area in Havrania (Nos. 10–16) and Kozinec (Nos. 17–22) part of Zázrivá (*Maps of Natural Radioactivity, 2009*).

Passive alpha track detector RamaRn (SÚJCHBO, Milín, Czech Republic), with Kodak LR 115 film located at the bottom of the diffusion chamber was used in this survey (*Thinová and Burian, 2008*). Two detectors were positioned in monitored buildings, primarily in the rooms situated on the ground floor, where the inhabitants spend most of their time. Detectors were placed 15–20 cm from the walls, as far as possible from the windows, doors and heating bodies. Building characteristics as building material, window tightness, cellar, year of construction and reconstruction, number of inhabitants, intensity of ventilation and time spent in monitored rooms were

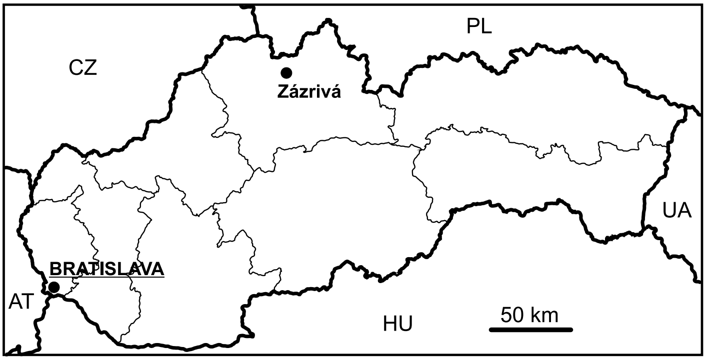

Fig. 1. Location of the studied area.

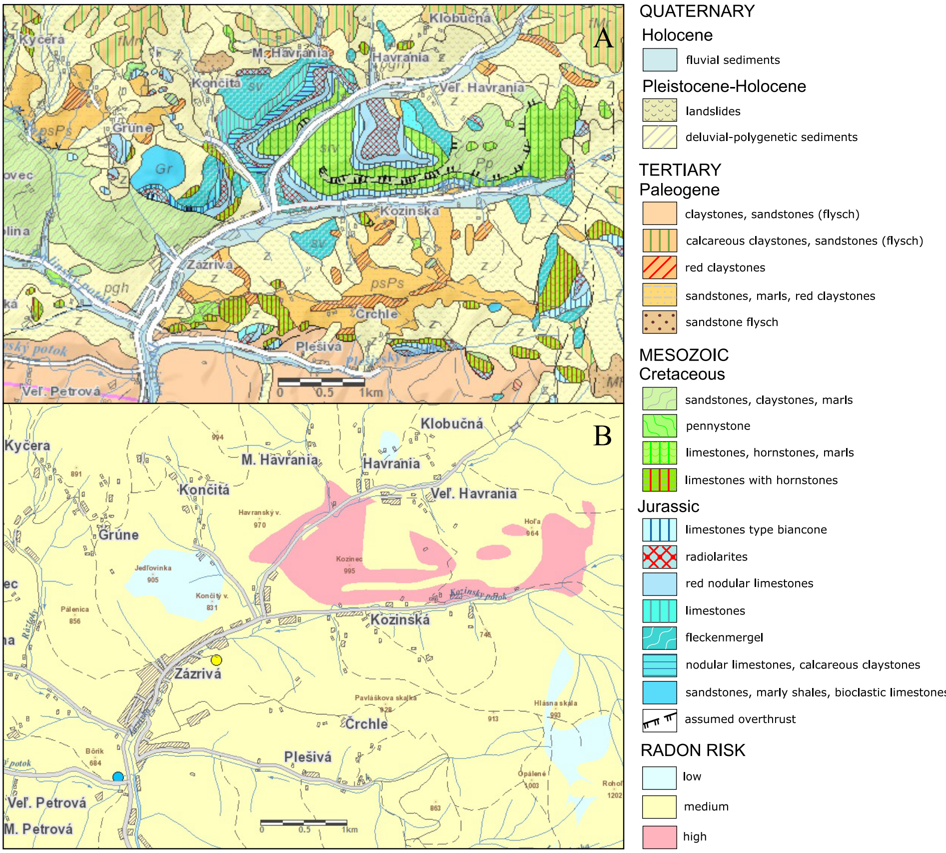

Fig. 2. Geological map (A) and radon risk map (B) of Zázrivá surroundings (modified according to *Geological map of Slovakia (2013)* M 1:50000 and *Maps of Natural Radioactivity (2009)*).

obtained through a questionnaire, distributed to the survey participants together with information leaflet about radon (*Müllerová et al., 2016*). After the collection the set of detectors was sent to the SÚJCHBO laboratory for an evaluation.

3. Results and discussion

In total, 184 detectors were distributed in Zázrivá during a one year survey and 177 (96%) were collected from the voluntary participants. In one of the monitored houses, both detectors were placed in rooms on the second floor, therefore these results were excluded, together with the results from six other rooms situated on the first floor. Only results obtained from ground-floor rooms were used in this paper. The final dataset consists of 149 results obtained in 38 rooms situated in 22 buildings, including kindergarten, based on four sets of collected detectors: 32 in summer, 37 in autumn, 38 in winter and 38 in spring. For rooms, where detectors were lost for one monitoring period, the annual average of RAC was calculated using seasonal correction factor (*Müllerová et al., 2022*).

Most of the collected detectors (74%) were placed in the kitchen, living room and bedroom. Aerated concrete and bricks prevailed among building materials. The majority of monitored rooms were equipped with PVC windows, however, the most of the houses were not thermally insulated (Table 1).

Table 1. Building characteristics.

Type of a room	rooms (%)	Building material	rooms (%)
kitchen	15 (40)	aerated concrete	12 (32)
living room	8 (21)	brick	9 (24)
bedroom	5 (13)	wood	4 (11)
classroom	2 (5)	stone	3 (8)
other	8 (21)	slag block	2 (5)
Construction period	**rooms (%)**	no info	2 (5)
1940–1950	6 (16)	other	6 (15)
1951–1970	10 (26)	**Thermal insulation**	**rooms (%)**
1971–1990	12 (32)	yes	12 (32)
1991–2000	3 (8)	no	22 (58)
after 2000	7 (18)	no info	4 (10)
Window tightness	**rooms (%)**	**Cellar**	**rooms (%)**
PVC windows	30 (79)	yes	13 (34)
old wooden windows	8 (21)	no	25 (66)

A histogram of the frequency distribution for annual average of RAC in monitored rooms is presented in Fig. 3. Radon activity less than 200 Bq/m^3

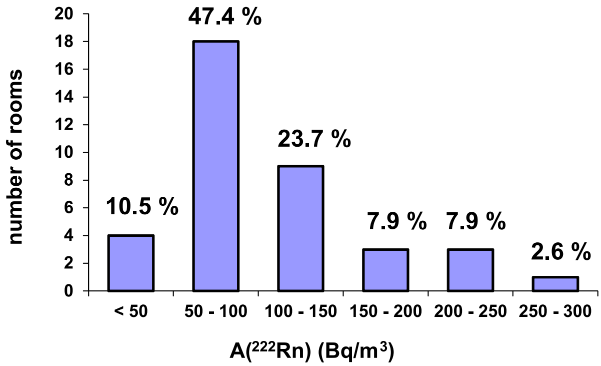

Fig. 3. The frequency distribution of annual indoor RAC in monitored rooms in Zázrivá.

was found in the majority of them (up to 90%) and the reference level of 300 Bq/m^3 recommended by the *Council Directive (2013)* 2013/59 was not exceeded.

Figure 4 depict the seasonal changes of indoor RAC using the notch-box diagram. The median is shown as an inside horizontal line, while the ends of the box indicate the 25th and 75th percentiles. The whiskers above and below the box correspond to the 90th and 10th percentiles, respectively.

In the majority of monitored buildings (74%) indoor radon minimum was found in summer season and maximum in autumn and winter months. Generally low radon levels during the summer period can be explained by

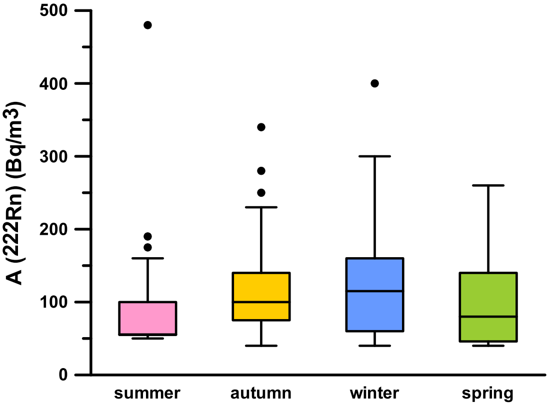

Fig. 4. Statistical distribution of indoor RAC according to the season of the year.

intensive ventilation of the rooms. All monitored buildings were mechanically ventilated, by opened windows. However, the highest radon level was found in this season equal to 480 ± 60 Bq/m^3. With exception of spring, in each monitoring campaign radon levels exceeding 300 Bq/m^3 were detected.

The results were examined in the respect of presence or absence of a cellar underneath the room and thermal retrofit of the building (Fig. 5) using the notch-box plots. Almost 34% of the monitored rooms in Zázrivá were situated above a cellar. RAC tends to be lower in these rooms, because the cellar usually protects the ground floor rooms from the direct soil airflow (*Papaefthymiou et al., 2003; Borgoni et al., 2014; Müllerová et al. 2016*). However, unless they are well insulated, cellars may sometimes serve as an entry point for radon into a building (*Buchli and Burkart, 1989*). Although RAC higher than 200 Bq/m^3 was found only in the rooms with direct contact with the subsoil, the graph shows that 95% confidence intervals of medians in no cellar and cellar groups overlap and therefore medians are considered the same within the confidence level.

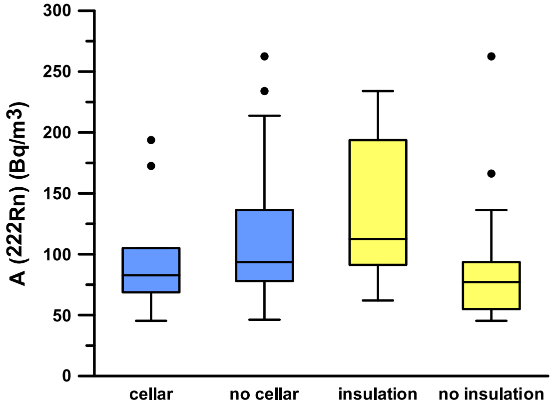

Fig. 5. The comparison of indoor ^{222}Rn concentration according to the presence/absence of cellar and thermal insulation.

Thermal retrofit works, such as window replacement and thermal insulation usually resulted in an increase of indoor RAC, due to reduction of air exchange rate of the house (*Collignan et al., 2016*). In Zázrivá, the distribution of indoor RAC between rooms in houses with and without thermal insulation shows that higher indoor values were found in thermally insulated buildings.

A possible influence of building material on indoor RAC was difficult to evaluate, because of small size of dataset and various kind of used materials. According to the questionnaire the majority of houses were built from aerated concrete and only in these houses annual average of indoor RAC exceeded 200 Bq/m^3. However, annual indoor RAC in these rooms ranged a wide span of values from 50 to 260 Bq/m^3.

Spatial distribution of the results of indoor RAC survey is depicted on Fig. 6. A visual comparison with radon risk map (Fig. 2B) did not reveal significantly elevated RAC in buildings situated in Kozinská part of Zázrivá. Although the highest indoor radon level (480 ± 60) Bq/m^3 was measured in the summer monitoring period, in house 20 in this part of Zázrivá, according to the questionnaire, this house was poorly ventilated, which probably caused an elevated indoor RAC, which was later not observed in other monitoring periods. Monitored house was relatively new, constructed in 2012 from a combination of wood and aerated concrete and has no cellar under the monitored rooms. Indoor RAC measured in other houses in Kozinská were similar to radon levels found in Havrania (Fig. 6A) and Central part of Zázrivá (Fig. 6B), which are situated in medium radon risk areas. A large part of Havrania is also situated in a high radon risk area, unfortunately most houses here were not permanently inhabited or measurements were not allowed by their owners, therefore indoor RAC was investigated solely in house 16. This house was built in 1940 from wood and did not underwent any kind of thermal retrofit, which may result in annual average of RAC less than 50 Bq/m^3 in both monitored rooms.

The highest annual average of indoor RAC among monitored houses was determined in a room of house 12 in Havrania part. It was constructed in 1980 from aerated concrete. Both monitored rooms were situated in a direct contact with the subsoil and indoor RAC exceeded 200 Bq/m^3 also in the second investigated room. This house was not thermally insulated.

Annual value of indoor RAC exceeding 200 Bq/m^3 was also found in both monitored rooms in house 7 situated in the Central part (Fig. 6B). This house was built in 1984 from aerated concrete, has no cellar and according to the questionnaire it was intensively ventilated.

In both classrooms of the kindergarten (No. 9) indoor RAC was less than 50 Bq/m^3. This building was made from bricks and concrete in 1989, has no cellar and did not undergo any kind of thermal retrofit.

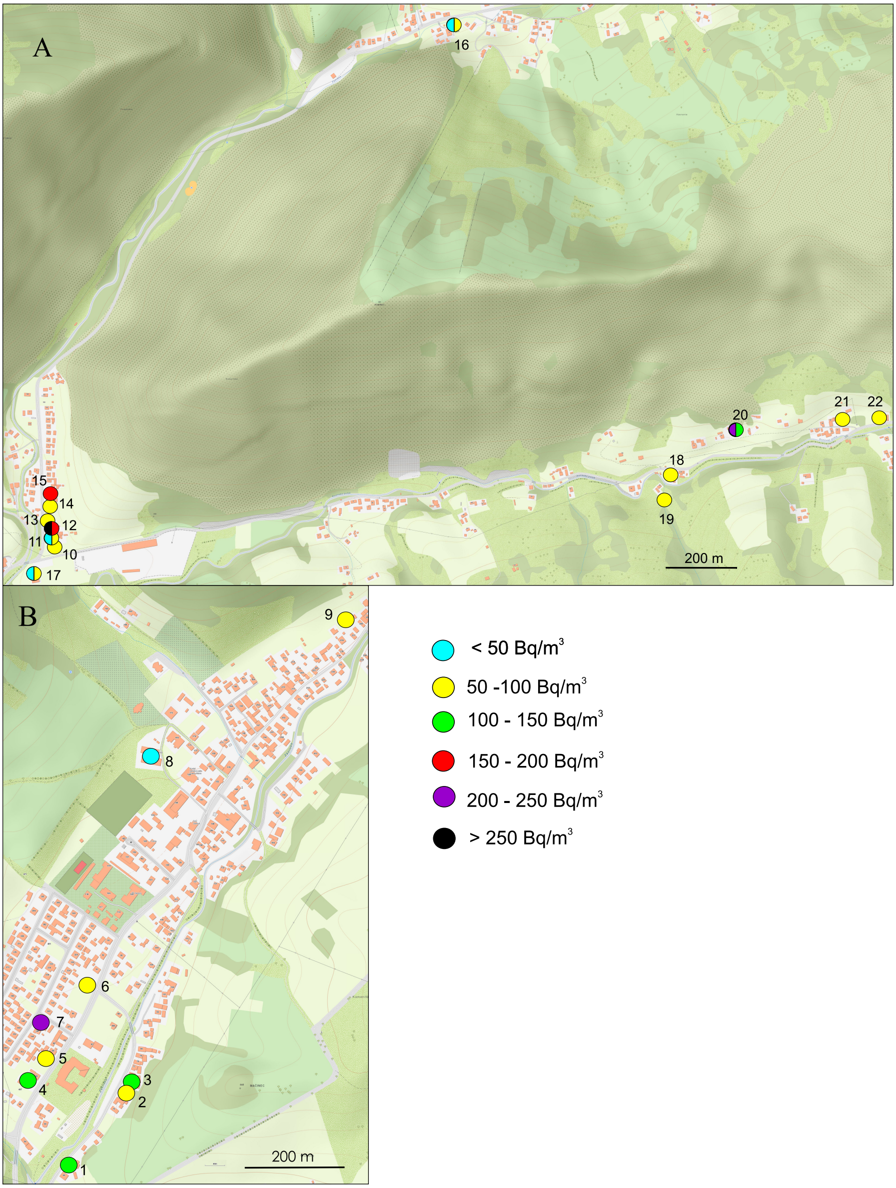

Fig. 6. Spatial distribution of annual average of indoor RAC in 22 monitored buildings in Kozinská and Havrania (A) and central part of Zázrivá (B) (modified according to *ZBGIS Mapka*, `https://zbgis.skgeodesy.sk`).

4. Conclusion

Possible influencing factors (fault, cellar, building material, thermal insulation) on indoor RAC were analysed. Annual radon levels exceeding 300 Bq/m^3 were not found in monitored buildings in Zázrivá. Indoor RAC in houses situated in a high radon risk area was of comparable level to houses situated in medium risk area. The results from this survey did not prove the possible influence of assumed fault zones crossing monitored area on indoor RAC levels in investigated rooms. From above mentioned also follows, that in terms of radon risk the monitored parts of village Zázrivá are safe for the residents.

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