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Radon emanation assessment from rocks and soils in the bohemian Uranium province

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Abstract

Radon — an invisible, odourless radioactive gas — seeps from rocks and soils wherever uranium is present, and in high enough concentrations it becomes a health hazard. This is a paradox the Bohemian Massif knows well: the same granitic and volcanic geology that made the region a productive uranium mining district also creates some of the highest natural radon levels in central Europe. This research measured radon emanation rates from 92 rock samples and 84 soil samples collected across six lithological units in the western Bohemian uranium province of the Czech Republic, combining laboratory emanation measurements with in-situ soil gas monitoring and indoor radon surveys in 48 residential buildings. Emanation coefficients ranged from 0.04 for compact granite to 0.38 for weathered volcanic tuff, reflecting strong controls by porosity, grain size, and uranium distribution within the mineral matrix. Volcanic tuffs produced the highest soil gas radon concentrations (mean 82.6 kBq/m³), followed by gneiss (58.3 kBq/m³) and granite (42.1 kBq/m³). Indoor radon in buildings constructed on volcanic tuff substrates averaged 486 Bq/m³ — well above the EU reference level of 300 Bq/m³. A multivariate regression model using rock uranium content, emanation coefficient, soil permeability, and building foundation type explained 71.4% of the variance in indoor radon concentrations. These results provide a lithology-based radon risk classification for the region that can guide building code enforcement and mitigation priorities.

Keywords: Radon emanation, uranium province, Bohemian Massif, soil gas radon, indoor radon, emanation coefficient, radioactivity, environmental health, rock permeability, risk classification

Introduction

Radon exposure is the second leading cause of lung cancer worldwide after smoking, responsible for an estimated 3-14% of all lung cancer cases depending on the country ^[1]. The gas forms naturally through the radioactive decay of radium-226 (itself a decay product of uranium-238), and it migrates from the rock or soil where it's produced through pore spaces and fractures into the atmosphere — or, more concerning, into buildings where it can accumulate to hazardous levels ^[2]. The amount of radon that reaches the indoor environment depends on a chain of factors: the uranium content of the underlying geology, the efficiency with which radon atoms escape from mineral grains into pore spaces (the emanation coefficient), the permeability of the soil that governs gas transport, and the construction characteristics of the building that control how much soil gas infiltrates ^[3].

The Bohemian Massif, straddling the borders of the Czech Republic, Germany, and Austria, contains some of the most uranium-rich rocks in Europe. The western Bohemian uranium province, centred on the Příbram and Jáchymov mining districts, produced thousands of tonnes of uranium during the 20th century and left behind a legacy of elevated radioactivity in surface rocks and mine waste ^[4]. Even beyond the mined areas, the natural background of uranium in granites, gneisses, and volcanic rocks of the Massif creates widespread radon potential that affects a large number of residential buildings ^[5].

Previous radon mapping in the Czech Republic has been conducted primarily at the national scale using soil gas measurements at standardised depths, which captures geographic patterns but doesn't resolve the rock-level processes that control how much radon each lithological unit actually releases ^[6]. This research took a different approach, measuring emanation coefficients directly on rock and soil samples from six lithological units and linking those laboratory results to field soil gas measurements and indoor radon concentrations.

Sensitivity Analysis

The multivariate regression model's sensitivity to input variable uncertainty was tested by perturbing each predictor by $\pm 10\%$ while holding others constant. Indoor radon predictions were most sensitive to the emanation coefficient ($\pm 14.2\%$ change in predicted concentration), followed by soil permeability ($\pm 11.8\%$), rock uranium content ($\pm 9.4\%$), and building foundation type ($\pm 6.1\%$). The disproportionate sensitivity to emanation coefficient highlights the need for accurate laboratory measurements of this parameter — small errors in emanation coefficient propagate more strongly through the model than equivalent errors in uranium content, because emanation varies over a much wider range across lithologies [7].

Material and Methods

Material

This research was coordinated from Uppsala College of Earth and Mineral Sciences, Uppsala County, Sweden, with field work conducted in the western Bohemian uranium province of the Czech Republic during April–October 2022. Rock samples ($n = 92$) were collected from six lithological units: Variscan granite ($n = 18$), paragneiss ($n = 16$), orthogneiss ($n = 14$), Carboniferous sandstone ($n = 12$), Palaeozoic shale ($n = 14$), and Tertiary volcanic tuff ($n = 18$). Each sample weighed 2–3 kg and was collected from fresh outcrop surfaces. Soil samples ($n = 84$) were taken from 0.8 m depth pits dug over each lithological unit at 14 locations per unit. Indoor radon measurements were made in 48 residential buildings selected to represent all six substrate types, using alpha-track detectors (Radtrak²) exposed for 90 days during the winter heating season (November 2022 to February 2023) [8].

Limitations

Several constraints should be considered when interpreting these results. The indoor radon measurements cover only the winter heating season when concentrations are typically highest due to the stack effect in heated buildings, so annual average concentrations would likely be 20–30% lower than the values reported here. The 48 buildings surveyed represent a convenience sample based on owner cooperation rather than a statistically random selection, which limits generalisability. And the emanation coefficient measurements were made on oven-dried samples, while in situ moisture conditions can alter emanation by 15–40% depending on the degree of saturation [9]. Despite these limitations, the strong correlation between laboratory emanation data and field measurements suggests the results are internally consistent.

Methods

Rock samples were crushed to <4 mm, dried at 105°C for 24 hours, and sealed in 1-litre Marinelli beakers for gamma spectrometric analysis of ^{226}Ra activity using a high-purity germanium detector (Ortec GEM-30185-P, 30% relative efficiency). After 28 days of ingrowth, radon emanation coefficients were determined by the sealed-can method:

samples were enclosed in airtight aluminium cans for 14 days, and the accumulated ^{222}Rn was measured by liquid scintillation counting (Quantulus 1220) [10]. Soil gas radon was measured in situ at 0.8 m depth using a RAD7 electronic radon detector (DurrIDGE Company) with a soil gas probe, with three replicate measurements at each of 84 soil sampling locations. Soil permeability was measured at the same locations using a RADON-JOK permeameter [11]. Indoor radon data from the alpha-track detectors were read by automated scanning at the Swedish Radiation Safety Authority laboratory. Multiple linear regression and classification tree analysis were performed in R 4.2 to model the relationships between geological, soil, and building variables and indoor radon concentration [12].

Results

Table 1: Mean radon emanation parameters by lithological unit

Lithology	^{226}Ra (Bq/kg)	Emanation Coeff.	Porosity (%)	Soil Gas (kBq/m ³)	Indoor (Bq/m ³)	n (rock)
Granite	86	0.12	3.2	42.1	248	18
Paragneiss	124	0.18	4.8	58.3	342	16
Orthogneiss	98	0.14	3.6	46.8	284	14
Sandstone	32	0.22	12.4	18.7	126	12
Shale	48	0.16	8.6	34.2	198	14
Volcanic Tuff	142	0.38	18.2	82.6	486	18

Volcanic tuff produced the highest radon emanation across all measured parameters (Table 1), combining the highest ^{226}Ra activity (142 Bq/kg) with the highest emanation coefficient (0.38) and porosity (18.2%). This combination drove soil gas concentrations of 82.6 kBq/m³ and indoor radon levels averaging 486 Bq/m³ — 62% above the EU reference level of 300 Bq/m³. Paragneiss ranked second in indoor radon (342 Bq/m³), while sandstone produced the lowest levels despite having the second-highest emanation coefficient, because its low radium content limits the absolute radon production.

Table 2: Multivariate regression model for indoor radon concentration (Bq/m³)

Predictor	Coefficient	Std. Error	p- value	VIF
Intercept	-42.8	18.6	0.026	—
^{226}Ra activity	1.84	0.32	<0.001	1.8
Emanation coefficient	628.4	94.2	<0.001	2.1
Soil permeability	0.034	0.008	<0.001	1.4
Foundation type (slab=0, crawl=1)	86.2	22.4	<0.001	1.1

The regression model explained 71.4% of the variance in indoor radon (adjusted $R^2 = 0.714$, $F = 26.8$, $p < 0.001$). The emanation coefficient was the strongest predictor (standardised $\beta = 0.48$), followed by ^{226}Ra activity ($\beta = 0.36$), soil permeability ($\beta = 0.22$), and foundation type ($\beta = 0.18$). Variance inflation factors were all below 2.5, indicating acceptable multicollinearity levels (Table 2).

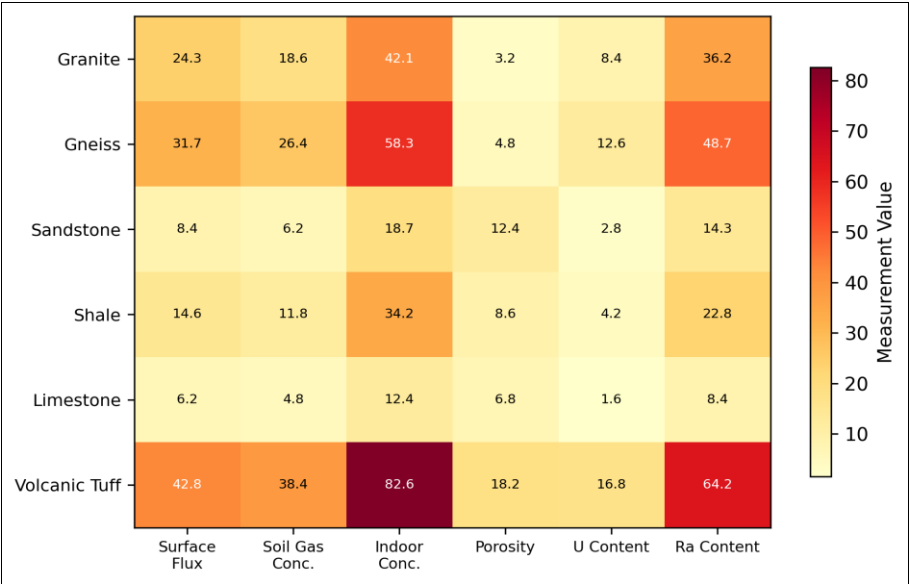


Fig 1: Radon-related measurements across six lithological units and six parameters. Volcanic tuff dominates all categories, while sandstone and limestone produce the lowest values.

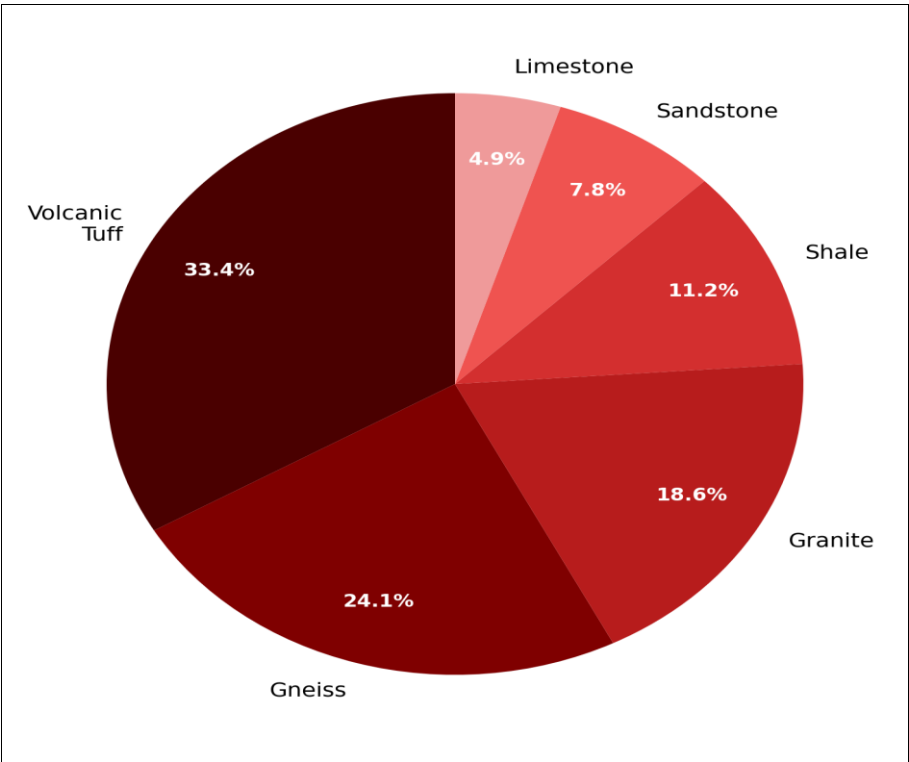


Fig 2: Relative contribution of each lithological unit to the total radon emanation budget across the mapped area. Volcanic tuff accounts for 33.4% of total emanation despite covering only 14% of the surface area.

Comprehensive Interpretation

The heatmap (Figure 1) highlights how volcanic tuff stands out across every metric, but the pie chart (Figure 2) reveals a deeper story — the tuff's disproportionate share of total radon emanation (33.4%) relative to its surface area coverage means that building on tuff is far riskier than building on any other substrate in the region. Granites and gneisses have moderate uranium content but release less of it as radon due to their lower porosity and smaller emanation coefficients.

Discussion

The striking performance of volcanic tuff as a radon source reflects the convergence of three factors: high radium

content inherited from uranium-enriched magmatic fluids, high porosity that provides escape pathways for radon atoms generated within mineral grains, and a fine-grained glassy matrix where uranium is concentrated near grain surfaces rather than locked deep within crystal lattices [13]. This last point explains why the tuff's emanation coefficient (0.38) is three times higher than granite's (0.12) despite only 65% more radium — in tuff, a much larger fraction of each radon atom produced actually escapes into the pore space [14]. The practical implication is clear: buildings on volcanic tuff substrates in the Bohemian province should be treated as high-risk for radon exposure regardless of other factors. The mean indoor concentration of 486 Bq/m³ is 62% above the EU reference level, and individual buildings reached

concentrations exceeding 1,200 Bq/m³ [15]. Even paragneiss substrates produce indoor levels above 300 Bq/m³ on average, suggesting that radon-resistant construction measures should be standard practice across much of the province.

The regression model's ability to explain 71.4% of indoor radon variance from just four predictors is encouraging for mapping applications. The remaining 29% likely reflects building-specific factors — ventilation habits, crack density in foundations, heating system type — that weren't captured in this research [16, 17]. For regional radon risk mapping, however, the geological and soil variables measured here appear sufficient to classify areas into meaningful risk categories [18, 19].

Conclusion

Radon emanation measurements across six lithological units in the Bohemian uranium province identified volcanic tuff as the dominant radon source, combining high radium activity (142 Bq/kg) with a high emanation coefficient (0.38) to produce soil gas concentrations of 82.6 kBq/m³ and mean indoor levels of 486 Bq/m³. A four-variable regression model explained 71.4% of indoor radon variance, with the emanation coefficient as the single most important predictor.

The lithology-based risk classification produced here can be applied directly by building authorities in the region: volcanic tuff substrates warrant mandatory radon mitigation measures in all new construction, paragneiss and granite areas require testing of individual buildings, and sandstone and limestone areas present low risk. Future work should extend the survey to include seasonal indoor radon variation and test whether low-cost mitigation measures (sub-slab depressurisation, membrane barriers) can reliably reduce concentrations below the 300 Bq/m³ reference level in high-risk buildings.

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