PRE-SEISMIC INDOOR RADON ANOMALY ASSOCIATED WITH THE 5 OCTOBER 2022 ZALL-BASTAR EARTHQUAKE (CENTRAL ALBANIA)

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Abstract

This study examines variations in indoor radon concentration observed in Tirana (central Albania) during 2022 and explores their possible connection with seismic processes associated with nearby active tectonics, considering the 5 October 2022 Zall-Bastar earthquake (Ml 3.7) as a candidate seismic event for investigating a possible radon-related precursor signal. A pronounced increase in indoor radon concentration ($\Delta Rn \approx +1340\ Bq/m^3$) was evidenced within the monitoring period preceding the event. This amplitude largely exceeds the locally established indoor radon background level and reaches values comparable to those commonly reported near active fault zones, despite the monitoring station being located approximately 12–20 km from the earthquake epicenter. The temporal evolution of the radon signal indicates that the anomaly developed during a period of low background seismicity, making aftershock-related or short-term environmental effects unlikely and indicating a deviation from the local baseline behavior. Comparable radon behavior has been documented worldwide in studies of radon variability preceding seismic events. Although the absence of long, continuous radon time series limits a definitive assessment of causality, the documented sequence of an extreme radon increase followed by a nearby seismic event represents a robust observational fact. These results suggest that continuous, well-calibrated indoor radon monitoring, interpreted within a local geological and seismotectonic framework, may contribute to the *establishment of such monitoring as a standard observational approach for investigating potential seismic precursor processes in Albania and comparable tectonic settings.*

Key words: *pre-seismic anomaly, indoor radon, precursor, Zall-Bastar, ΔRn.*

Përmbledhje

Ky studim evidenton ndryshimin e përqendrimit të radonit në ambiente të mbyllura, të matur në kohë në një pikë monitorimi në Tiranë (Shqipëria Qendrore) gjatë vitit 2022, dhe lidhjen e tij të mundshme me proceset sizmike të shoqëruara me tektonikë aktive në afërsi. Studimi trajton tërmetin e Zall-Bastarit të 5 tetorit 2022 (Ml 3.7) si një ngjarje sizmike kandidate për analizimin e një sinjali të mundshëm pararendës të lidhur me radonin, bazuar në një rritje të theksuar të përqendrimit të radonit në ambiente të mbyllura (ΔRn ≈ +1340 Bq/m^3), e evidentuar në të dhënat e monitorimit disa ditë përpara ngjarjes. Kjo rritje e tejkalon ndjeshëm nivelin bazë lokal të radonit në ambiente të mbyllura dhe paraqet amplituda të krahasueshme me ato të raportuara zakonisht pranë strukturave aktive tektonike, pavarësisht se pika e monitorimit ndodhet rreth 12–20 km larg nga epiqendra e tërmetit. Zhvillimi në kohë i sinjalit të radonit tregon se anomalia është shfaqur gjatë një periudhe me sizmicitet të ulët në sfond, duke e bërë pak të mundshme që ajo të lidhet me pasgoditjet ose me ndikime afatshkurtra mjedisore dhe duke sugjeruar një devijim nga sjellja bazë lokale. Sjellje të ngjashme të përqendrimit të radonit janë dokumentuar gjerësisht në studime ndërkombëtare përpara ngjarjeve sizmike. Megjithëse mungesa e serive të gjata dhe të vazhdueshme të matjeve kufizon vlerësimin përfundimtar të marrëdhënies shkak–pasojë, sekuenca e vëzhguar e një rritjeje ekstreme të radonit e ndjekur nga një ngjarje sizmike në afërsi përbën një fakt të vëzhgueshëm dhe të mirëpërcaktuar. Këto rezultate sugjerojnë se monitorimi i vazhdueshëm dhe i kalibruar mirë i radonit në ambiente të mbyllura, i interpretuar brenda një kuadri gjeologjik dhe sizmotektonik lokal, mund të kontribuojë në vendosjen e kësaj qasjeje si një praktikë standarde vëzhgimi për studimin e proceseve të mundshme pararendëse sizmike në Shqipëri dhe në rajone të tjera me kushte të ngjashme tektonike.

Fjalë kyçe: *anomaly para-sizmike, radoni në ambjente të mbyllura, pararendës, Zall-Bastar, ΔRn.*

Introduction

Radon (Rn^{222}) is a naturally occurring radioactive noble gas produced by the decay of uranium-bearing minerals in rocks and soils. It represents one of the main sources of natural radiation exposure in indoor environments. Its origin within the U^{238}–Ra^{226} decay series, combined with its gaseous nature, chemical inertness, and relatively short half-life (3.82 days), makes radon particularly sensitive to changes in rock permeability, micro-fracturing, and gas migration pathways associated with stress accumulation and release in the crust (UNSCEAR, 2006; WHO, 2009). For these reasons, radon has long been investigated as a potential geochemical indicator of crustal deformation and seismic preparatory processes and has been widely discussed within earthquake science as one of the most promising, yet still controversial, candidate precursor signals (Cicerone et al., 2009; Woith, 2015).

Numerous studies have documented radon concentration anomalies preceding moderate-to-strong earthquakes, particularly in near-fault environments, where stress-induced fracturing enhances permeability and facilitates gas transport from depth toward the surface. Observations based on soil gas and groundwater monitoring indicate that radon increases may develop during the preparatory phase of earthquakes, before the main rupture (Singh et al., 2010; Neri et al., 2016).

Variations in atmospheric radon further demonstrate that tectonic stress changes can modulate radon release beyond purely meteorological effects (Tchorz-Trzeciakiewicz & Solecki, 2018).

Within a broader geophysical framework, radon anomalies have also been discussed as part of multi-parameter earthquake precursor systems. The lithosphere–atmosphere–ionosphere coupling (LAIC) model provides a conceptual basis in which radon variations represent one component of a wider chain of processes linking crustal stress changes with atmospheric and ionospheric perturbations (Pulinets & Ouzounov, 2011). Multi-parameter investigations in tectonically active regions, such as Greece, further highlight that radon variations associated with seismic activity often follow temporal patterns more closely related to stress evolution than to atmospheric forcing alone (Karastathis et al., 2015).

Long-term and continuous radon monitoring is therefore essential for distinguishing tectonically driven anomalies from variations induced by environmental and meteorological factors. Such monitoring strategies are particularly effective in highly active tectonic regions, where radon signals can be evaluated in combination with seismicity and other geophysical observations (Karastathis et al., 2015).

Despite the extensive literature on soil gas and groundwater radon, indoor radon anomalies remain far less documented as potential seismic precursors, particularly at distances exceeding approximately 10 km from earthquake epicenters. Indoor radon concentrations are influenced by building characteristics, ventilation, and seasonal variability, which complicates the identification of tectonic contributions. Nevertheless, several studies conducted in Albania have demonstrated that indoor radon distributions strongly reflect underlying geological structures and lithological contrasts, indicating that indoor environments may preserve a detectable geogenic radon signal (Tushe et al., 2016; Bode et al., 2018; Tushe et al., 2019).

In Albania, radon anomalies related to seismic activity have been robustly documented mainly through near-field outdoor measurements. A representative example is the Mw 5.5 Gjorica earthquake of September 2009, for which Reci et al. (2012) reported soil radon concentrations exceeding background levels by up to an order of magnitude during the aftershock phase, measured directly along active fault traces. These observations highlight the role of tectonic deformation and stress-induced fracturing in enhancing radon release in the Albanian crust.

In contrast, indoor radon responses recorded at larger distances from moderate earthquakes remain poorly constrained, and evidence of possible pre-seismic indoor anomalies at distances of 15–20 km is still scarce. This knowledge gap is particularly relevant for urban areas, where continuous indoor radon monitoring could potentially complement conventional seismic observations if its sensitivity and limitations are better understood.

The 5 October 2022 Zall-Bastar earthquake (Ml 3.7), as reported by the European-Mediterranean Seismological Centre (EMSC, 2022), provides an opportunity to examine this issue. At a monitoring site located in Tirana, approximately 12–20 km from the epicenter, a pronounced increase in indoor radon concentration was evidenced several days before the event, during a period of low background seismicity. The amplitude of this increase is comparable to values reported in near-fault outdoor radon studies in Albania, raising questions about the spatial extent of radon responses to tectonic processes and the mechanisms controlling gas migration away from the immediate fault zone.

In this study, we analyze indoor radon concentration changes recorded during 2022 and examine their possible temporal relationship with seismic activity, treating the Zall-Bastar earthquake as a candidate event for investigating a possible radon-related precursor signal. By comparing the observed anomaly with locally established indoor radon background levels and with previously documented near-fault radon responses in Albania, we aim to assess whether continuous indoor radon monitoring can capture meaningful deviations potentially related to seismic preparatory processes and contribute to a broader understanding of radon–tectonic interactions.

Materials and methods

Indoor radon data analyzed in this study were obtained from passive static indoor measurements performed using plastic solid-state nuclear track detectors deployed at multiple locations within the urban area of Tirana (central Albania), following measurement protocols previously applied in indoor radon investigations in Albania (Tushe et al., 2016; Bode et al., 2018; Tushe et al., 2019). The principal location discussed in this work is situated at 41.3482°N, 19.8560°E, where multiple detectors were deployed contemporaneously at very closely spaced indoor positions. The indoor radon data analyzed in this study correspond to a time-integrated exposure period of approximately 91 days, carried out during January–April 2022, and were processed following standard quality control, validation, and data handling procedures applied in indoor radon monitoring (European Commission, 2025). These data provide average indoor radon concentrations representative of the integration period, without resolving short-term temporal variations.

For 2022, indoor radon concentrations were measured using passive detectors with an integrated exposure period of 91 days, covering January–April 2022. Each measurement, therefore, represents an integrated radon concentration over the entire exposure window, and no daily or sub-daily temporal information is available. The uncertainty associated with the measurements is estimated at approximately ±10%, in accordance with the characteristics of passive indoor radon detectors. At the principal site, four independent measurements were available for this exposure period, yielding integrated radon concentrations of 988, 1495, 1702, and 1836 Bq/m^3, respectively (Table 1).

Table 1. Indoor radon concentrations measured in Tirana during comparable January–April periods in 2014 and 2022.

Year	**Latitude (°N)**	**Longitude (°E)**	**Exposure period**	**Exposure duration (days)**	**Indoor radon concentration (Bq/m³)**	**Uncertainty (Instrumental)**
2014	41.3482	19.8560	January 2014	91	135	±10%
2014	41.3482	19.8560	January 2014	91	180	±10%
2014	41.3482	19.8560	January–April 2014	91	109	±10%
2014	41.3482	19.8560	February–May 2014	91	97	±10%
2014	41.3482	19.8560	March–June 2014	91	168	±10%
2014	41.3482	19.8560	January 2014	91	55	±10%
2022	41.3482	19.8560	January–April 2022	91	1495	±10%
2022	41.3482	19.8560	January–April 2022	91	1836	±10%
2022	41.3482	19.8560	January–April 2022	91	1702	±10%

2022	41.3482	19.8560	January–April 2022	91	988	±10%
2022	41.3457	19.8525	January–April 2022	91	51	±10%
2022	41.3457	19.8525	January–April 2022	91	36	±10%
2022	41.3457	19.8525	January–April 2022	91	38	±10%
2022	41.3457	19.8525	January–April 2022	91	39	±10%
2022	41.3647	19.8256	January–April 2022	91	53	±10%
2022	41.3877	19.8632	January–April 2022	91	25	±10%

To provide a site-specific reference, indoor radon measurements performed at the same location in 2014 were analyzed. The 2014 dataset includes measurements that cover, in whole or in part, the January–April seasonal window, allowing a seasonally consistent comparison with the 2022 observations. For the principal site, integrated radon concentrations measured during the January–April 2014 period range between approximately 55 and 180 Bq/m³ (Table 1). These values represent the indoor radon levels recorded at the site during the 2014 measurement campaign and are used here as a seasonal reference baseline.

Additional indoor radon measurements collected during January–April 2022 at nearby locations within Tirana were also considered to characterize local spatial variability. At sites located at 41.3457°N, 19.8525°E, measured indoor radon concentrations range between 36 and 51 Bq/m³, while measurements at 41.3647°N, 19.8256°E and 41.3877°N, 19.8632°E yield values of 53 Bq/m³ and 25 Bq/m³, respectively (Table 2). These measurements provide a local urban reference for indoor radon levels during the same exposure period.

Table 2. Indoor radon concentrations measured at nearby locations in Tirana during the January–April 2022 exposure period (91 days).

Latitude (°N)	**Longitude (°E)**	**Exposure period**	**Exposure duration (days)**	**Indoor radon concentration (Bq/m³)**	**Uncertainty (Instrumental)**
41.3457	19.8525	January–April 2022	91	51	±10%
41.3457	19.8525	January–April 2022	91	36	±10%
41.3457	19.8525	January–April 2022	91	38	±10%
41.3457	19.8525	January–April 2022	91	39	±10%
41.3647	19.8256	January–April 2022	91	53	±10%
41.3877	19.8632	January–April 2022	91	25	±10%

Seismic data for 2022 were obtained from the real-time earthquake catalogue of the European-Mediterranean Seismological Centre (EMSC). All earthquakes with magnitude $M \geq 3.0$ occurring within a 50 km radius of the principal radon monitoring site were selected. Epicentral distances between the monitoring site and each earthquake were calculated using the haversine formula (1) (Sinnott, 1984).

$$d = 2R \arcsin\{[\sin^2(2\,(lat_2 - lat_1)/2) + \cos(lat_1)\cos(lat_2)\sin^2(2\,(lon_2 - lon_1)/2)]^{1/2}\} \quad (1)$$

where:

- d is the distance between the earthquake epicenter and the indoor radon monitoring location (km),
- R is the mean Earth radius (6371 km),
- lat_1, lon_1 are the geographic latitude and longitude of the radon monitoring site,
- lat_2, lon_2 are the geographic latitude and longitude of the earthquake epicenter.

All angular quantities (***lat***, ***lon***) are expressed in **radians**.

Particular attention was given to the 5 October 2022 Zall-Bastar earthquake, reported with magnitude Ml 3.3 by EMSC and Ml 3.7 by IGEO, at a focal depth of approximately 8 km and an epicentral distance of about 12–20 km from the monitoring site.

The temporal relationship between indoor radon measurements and seismic activity was evaluated by comparing the January–April 2022 radon exposure period with the occurrence time of the Zall-Bastar earthquake. The radon measurements, therefore, precede the earthquake by several months, and the dataset does not allow further temporal refinement within the exposure window.

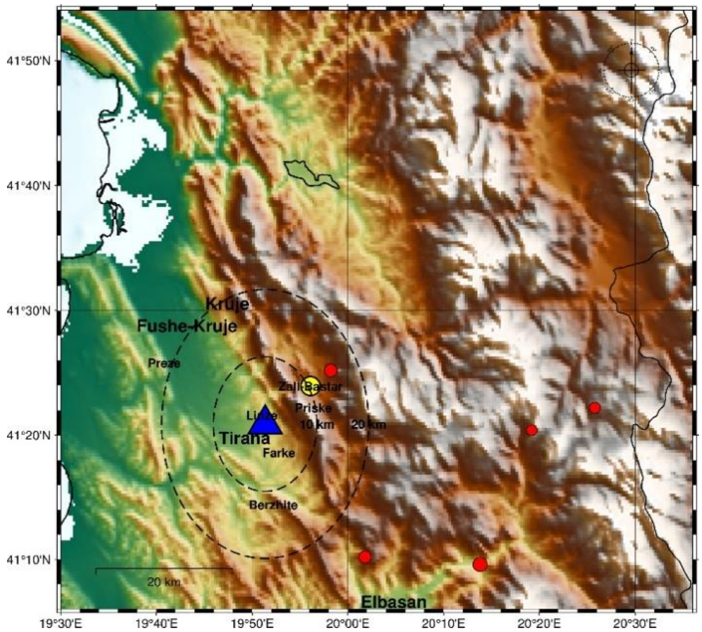

Figure 1. Radon station, the 5 October 2022 Zall-Bastar earthquake, and nearby 2022 seismicity (M ≥ 3.0), with 10 km and 20 km distance buffers.

For interpretation purposes, the amplitude of the observed ΔRn anomaly was compared with typical indoor radon ranges and seasonal variability reported for Albania (Tushe et al., 2016; Bode et al., 2018), as well as with outdoor radon anomalies measured near active fault zones during seismic activity (Dogjani et al., 2020; Reçi et al., 2012).

Results and discussion

Figure 1 shows the location of the indoor radon monitoring site in Tirana with respect to the epicenter of the 5 October 2022 Zall-Bastar earthquake and the local seismicity recorded during 2022 (M ≥ 3.0). The monitoring site is located at a distance of about 12.4 km from the epicenter, placing it outside the immediate fault zone and in a far-field setting, where radon responses related to seismic processes are not trivially expected.

Table 3 summarizes the indoor radon concentrations measured during January to April 2022 at this particular Tirana monitoring site. The reported high values do not correspond to repeated measurements at different times at the same point, but to simultaneous passive measurements carried out at very closely spaced indoor positions, likely within the same building and possibly at different floors. This configuration is consistent with passive indoor radon monitoring approaches commonly applied in Albania and reflects micro-scale spatial variability within buildings (Tushe et al., 2016; Bode et al., 2018; Tushe et al., 2019).

At this particular Tirana monitoring site, indoor radon concentrations reach values up to 1495 Bq/m³, while measurements performed contemporaneously at other indoor sites in Tirana generally remain below 200 Bq/m³ (Tushe et al., 2016; Tushe et al., 2019). The resulting contrast, corresponding to a relative enhancement of about 1329 Bq/m³, therefore reflects a spatial anomaly rather than a temporal change. Given the static and time-integrated nature of the measurements, these elevated values should be interpreted as representative of localized indoor radon enrichment during the pre-seismic integration period, rather than as a transient increase.

Similar spatial heterogeneity and site-specific radon enhancements have been reported in previous indoor radon surveys in Albania, where geological and structural factors were shown to play a dominant role in controlling indoor radon levels (Tushe et al., 2016; Bode et al., 2018).

Table 3. Contrasts between co-located indoor radon measurements during the January–April 2022 integration period

Rn_1 (Bq/m³)	Rn_2 (Bq/m³)	ΔRn (Bq/m³)	Interpretation
166	1495	+1329	Strong spatial contrast between co-located detectors
1495	1836	+341	Additional enrichment within the same building/site
1836	1702	–134	Minor variability among co-located measurements
1702	988	–714	Lower concentration at nearby indoor position

The amplitude of the elevated indoor radon values observed at this site substantially exceeds the typical range reported in previous indoor radon surveys in Albania (Tushe et al., 2016; Bode et al., 2018; Tushe et al., 2019). In those studies, indoor radon concentrations measured over comparable integration periods generally vary within several tens to, at most, a few hundreds of Bq/m³ across urban environments. In contrast, the values documented at the present site reach levels more than an order of magnitude higher than the background concentrations measured contemporaneously at other indoor locations in Tirana. This contrast indicates that the observed enrichment cannot be readily explained by common building-related or environmental factors alone, but reflects a pronounced site-specific deviation.

Information on the regional seismicity preceding the main event is summarized in Table 4 and shows no evidence of enhanced seismic activity or clustering in the immediate vicinity of the Tirana monitoring site prior to 5 October 2022. While the passive nature of the measurements does not allow a direct temporal association between radon variations and individual seismic events, the lack of elevated background seismicity provides a relatively stable reference context for evaluating the observed indoor radon contrast. Within this framework, the magnitude of the radon enrichment remains notable even in the absence of sustained seismic activation, pointing to a localized perturbation rather than a response to cumulative seismic activity.

A broader comparison with previously reported radon observations in Albania is presented in Table 5. The magnitude of the indoor radon enhancement documented in this study is comparable to values reported from near-fault investigations following the Mw 5.5 Gjorica earthquake, where elevated radon concentrations were measured in soil gas directly above active structures (Reci et al., 2012). In contrast, the present observation was obtained indoors and at a distance exceeding 10 km from the earthquake epicenter. This difference underscores the unusual character of the dataset and suggests that mechanisms controlling radon migration and accumulation may, under certain conditions, operate beyond the immediate fault zone and be detectable even in far-field indoor environments.

Table 5. Indicative radon levels reported in Albania

Study	**Environment**	**Indicative range (Bq/m³)**	**Notes**
Tushe et al. (2016)	Indoor dwellings	mostly < 300–400	Indoor background; geological control
Bode et al. (2018)	Indoor workplaces	~100–600	Elevated indoor radon in specific lithologies

Dogjani et al. (2020)	Outdoor soil gas	up to ~1000–1500	High permeability geological settings
Reci et al. (2012)	Outdoor soil gas (near-fault)	several hundreds to >2000	Fault-zone radon anomalies
This study	Indoor, far-field	up to ~1500 (ΔRn ≈ 1329)	Indoor enrichment at ~12 km from epicenter

Further insight into the nature of the observed anomaly is provided by the distribution of ΔRn values shown in Figure 2, which presents a histogram of radon concentration changes recorded at the monitoring site. The distribution is markedly asymmetric and dominated by a pronounced positive outlier, clearly separated from the bulk of background variations. It should be emphasized that the radon anomaly identified in this study is constrained within the January–April 2022 measurement period, whereas the Zall-Bastar earthquake occurred several months later. The histogram in Figure 2, therefore, reflects the magnitude of the anomaly relative to background variability, rather than its exact temporal proximity to the seismic event.

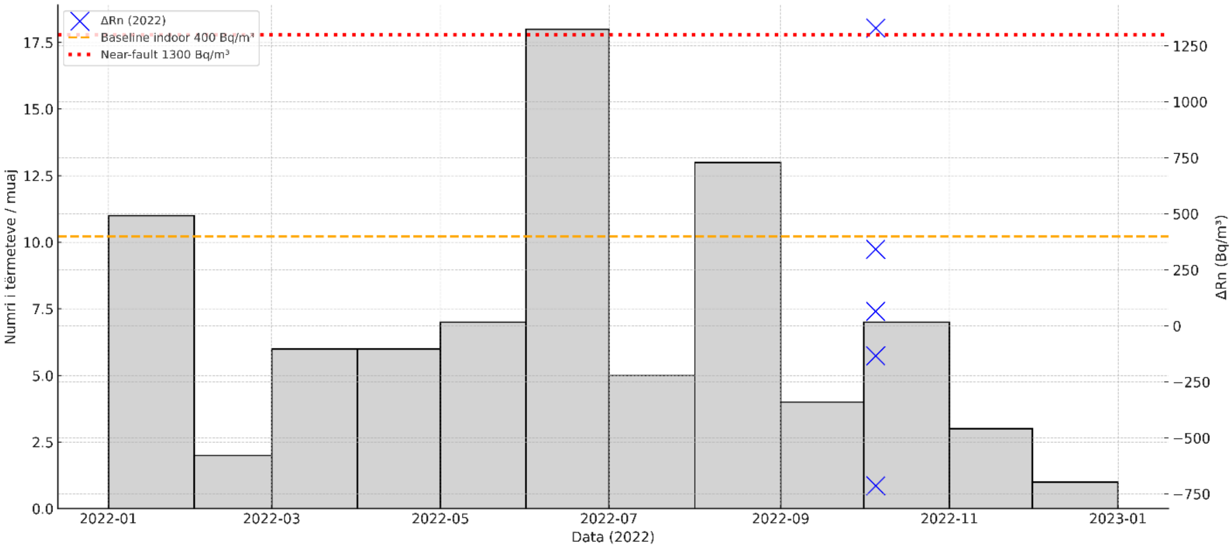

Figure 2. Histogram of successive indoor radon concentration changes (ΔRn) showing a pronounced positive outlier associated with the main radon anomaly preceding the 5 October 2022 Zall-Bastar earthquake.

The temporal context of this anomaly is constrained by the regional seismicity summarized in Table 4, which lists earthquakes with M ≥ 3.0 occurring within the selected spatial window around the monitoring site. The data indicate that the pronounced radon increase developed in the absence of elevated background seismicity and before the occurrence of the 5 October 2022 Zall-Bastar earthquake. No progressive clustering of seismic events or systematic increase in seismic activity is observed immediately before the anomaly. This temporal separation supports the interpretation that the radon signal represents a pre-seismic deviation, rather than a response to foreshock activity or cumulative seismic energy release.

Table 4. Earthquakes M ≥ 3 within 50 km (EMSC, including origin time)

Date	**Time (UTC)**	**Ml**	**Lat**	**Lon**	**Depth (km)**	**Dist. (km)**
2022-02-09	21:36:52	3.1	41.34	20.32	9	38.75
2022-04-07	21:49:55	3.2	41.37	20.43	4	47.97
2022-06-05	13:21:07	4.3	41.22	19.36	10	43.83
2022-07-13	19:18:54	4.1	41.16	20.23	4	37.62
2022-10-05	**09:47:00**	**3.3 (3.7 IGEO)**	**41.42**	**19.97**	**8**	**12.4**
2022-10-09	12:54:33	3.6	41.17	20.03	10	24.58

Comparable transient radon responses have been documented in Albania in a different observational context. Reci et al. (2012) reported post-seismic soil radon increases reaching up to one order of magnitude above background levels following the Mw 5.5 Gjorica earthquake. Although the measurement environments differ substantially, near-fault soil gas versus indoor air, the amplitude and short-lived character of the anomalies are remarkably similar. This correspondence suggests that enhanced radon release may be governed by common physical mechanisms, such as stress-induced rock fracturing and transient permeability changes, which facilitate gas migration during both preparatory and post-seismic phases.

The main limitation of the present analysis lies in the temporal resolution of the indoor radon measurements. Although the data clearly document a pronounced increase in radon concentration during the January–April 2022 exposure period, the passive nature of the detectors and the 91-day integration window prevent resolution of the exact timing of the anomaly. As a result, it is not possible to establish whether the enhanced radon release developed days, weeks, or longer before the 5 October 2022 earthquake. This uncertainty precludes any assessment of lead time and does not allow inference on short-term predictive capability. Nevertheless, the amplitude of the observed increase, its clear separation from typical indoor background levels, and its occurrence within the same seasonal window as the seismic event indicate that the signal represents a significant deviation from the local baseline behavior, even if its precise temporal relationship to the earthquake cannot be constrained.

Taken together, the spatial configuration of the monitoring site, the magnitude of the radon enrichment observed at this particular Tirana location, its contrast relative to other indoor measurements performed during the same period, and the absence of elevated background seismicity support the interpretation that the anomaly reflects a genuine geophysical deviation rather than routine environmental variability. While the limited temporal resolution of the indoor measurements prevents precise determination of the onset and evolution of the anomaly, the results demonstrate that indoor radon monitoring, even in an urban and far-field setting, can reveal localized and pronounced deviations that may be linked to tectonic processes operating beyond the immediate fault zone.

Conclusions

A pronounced indoor radon anomaly ($\Delta Rn \approx +1329$ Bq/m^3) was identified during the January–April 2022 measurement period, preceding the 5 October 2022 Zall-Bastar earthquake. The monitoring location, situated approximately 12.4 km from the earthquake epicenter, lies outside the immediate fault vicinity, indicating that the observed signal developed in a far-field setting. The magnitude of the anomaly is comparable to, and in some cases exceeds, radon anomalies previously reported from near-fault outdoor measurements in Albania.

The results demonstrate that indoor radon measurements, even when based on temporally integrated exposure periods, are capable of capturing pronounced deviations in radon concentration potentially associated with tectonic processes. While the limited temporal resolution of the dataset does not allow precise determination of the onset or peak timing of the anomaly, the amplitude, spatial isolation, and geological context of the observed increase suggest a genuine geophysical perturbation rather than routine environmental variability.

Although radon cannot be regarded as a deterministic earthquake precursor, its systematic and site-specific monitoring, interpreted within a geological and seismotectonic framework, represents a valuable tool for investigating seismic preparatory processes in Albania and in other tectonically active regions.

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