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研究課題名（和文）Spatial distribution of radon and thoron in the soil around active faults as a contribution to the elevated indoor radon

研究課題名（英文）Spatial distribution of radon and thoron in the soil around active faults as a contribution to the elevated indoor radon

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研究成果の概要（和文）：ラドンは土壌や岩石等から自然に発生する放射性ガスであり建物内に蓄積する。長期間吸入すると肺がんを含む重大な健康リスクをもたらす可能性がある。高ラドン濃度が発生する可能性のある活断層近辺において、ラドン濃度と土壌および下層土を調査した。断層からの距離ならびに二酸化炭素(CO2) 濃度とラドン濃度の間に強い相関関係が観察された。ラドンがCO2のようなキャリアガスによって深部から輸送され、亀裂構造による高い土壌透過性が示唆された。ラドン指数（RI）に基づいてサイトを分類し、地質ラドンポテンシャルを算出することができた。日本の地質学的特性により、より多くのサイトが高いRIゾーンに分類されると予想される。

研究成果の学術的意義や社会的意義
本研究で示した土壌中のラドンや二酸化炭素の濃度と土壌透過性を関連付ける野外調査データは、日本全土の包括的な地質ラドンポテンシャルマップの作成に貢献すると考えられる。このようなマップは、ラドン曝露からの公衆安全を確保するために活用されるとともに、ラドンレベルの潜在的変動を評価するための地質学的ハザード研究に資する。マップ化により高リスク地域であることがわかれば、新しい建物を建設する際に、屋内でのラドンガスの蓄積を防ぐための積極的なアプローチを実施することができるようになる。

研究成果の概要（英文）：Radon (Rn) is a radioactive gas that naturally emanates from the decay of uranium in soil, rock, and water. It can accumulate in buildings, posing significant health risks, including lung cancer, especially with prolonged exposure.
Radon concentrations, along with related parameters such as CO2 levels and soil permeability, were investigated in soil and subsoil near active faults where high radon concentrations may occur. A strong correlation was observed between the distance from the fault and the concentrations of both CO2 and radon. It is suggested that radon is transported from deep layers within the soil by a carrier gas like CO2, and that high soil permeability is due to the fracture structure. Sites were classified based on the radon index (RI), and the geological radon potential was calculated. Due to Japan's geological characteristics, it is expected that more sites will be classified into the high RI zone.

研究分野：radiation

キーワード：radon　thoron　carbon dioxide　soil permeability　radon modelling

１．研究開始当初の背景

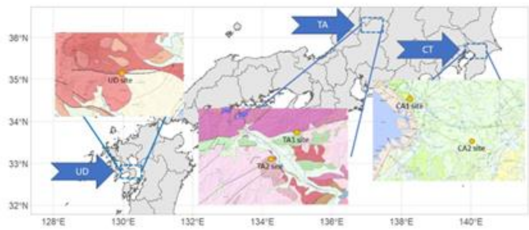
Soil is a major source of the natural radioactive gases as radon (^{222}Rn, Rn) and thoron (220Rn or denoted as Tn). Due to its lengthy half-life (3.825 days), radon proves valuable in geological hazard detection, such as identifying active faults, volcanic activity, or predicting earthquakes[1]. The relationship between soil and indoor radon concentrations is complex, influenced by various parameters[2]. Increased radon concentrations have been found near faults, however is not uniformly distributed at all faults, and the mechanism behind this increase remains under debate[3]. Hence, investigating radon levels in soil near tectonic faults in Japan is advisable.

２．研究の目的

This study focuses on analyzing results from *in-situ* measurement campaigns assessing soil gas concentrations of radon, thoron, and CO_2, alongside soil permeability measurements, conducted across two distinct regions of Japan with active faults and one without. The primary objectives include examination whether active faults show increasing of Rn concentrations in soil and application of the diffusion-advection Rn transport model in for predicting Rn release to the atmosphere and entry indoors in the area with potentially high geohazard risk.

３．研究の方法

Three measurement sites, namely UD, TA, and CT with different geological structures were selected on the basis of previous Rn indoor national survey [4] in combination with geology and tectonic of the areas.



The UD site (Akamatsudani Fault, Lat: 32.74454, Long: 130.3196) is located on the slope of the active Unzen volcano in the western part of Kyushu Island, which last erupted in November 1990.

Figure 1. Location of measurement sites

In the Takayama area located in the Hida Massif, two sites, TA1 (Taiei fault, GPS: 36.2619, Long: 137.2041) and TA2 (Azehata Fault, GPS: 36.2333, 137.1728) were selected to the North of Takayama City. The sites are in forested soils and remantled material at TA1 site, while it is forest soil and agricultural soils at TA2. The CT test site in Chiba Prefecture is located in an area with no active faults.

Two geophysical methods, i.e. ground penetrating radar and handheld magnetometer in conjunction with a standard geotechnical cone penetrometer were used to determine the subsurface structure and soil characteristics of the area as well as to identify the positions and routes of predicted faults.

The measurement system is presented in Figure 2. Rn and Tn concentration in soil gas were measured using active instrument (RAD7, Durridge, USA). The measurement set-up consisted of an active

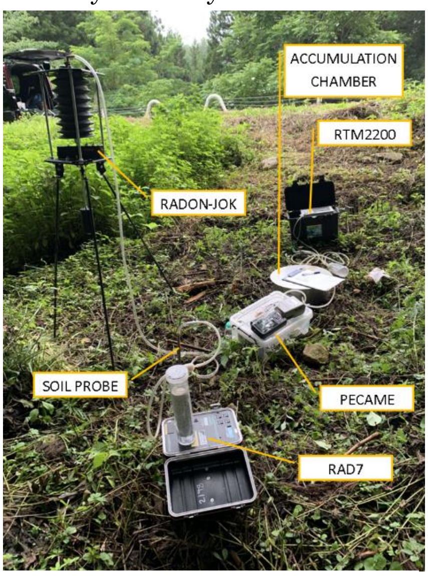


Figure 2. Measurement system

device and a 1.10 m soil-gas probe. The soil probe was installed in the ground in most points at a depth of about 50 - 60 cm, due to the soil structure (rocks and stones). Measurement of the Rn and Tn exhalation rates from the surface was carried out through the accumulation of gas inside the chamber and measured by active device (RTM2000, Sarad, Germany). Soil permeability and CO_2 were measured at the same points as Rn and Tn using RADON-JOK and PECAME (a newly developed device for parallel measurement of permeability and CO_2 concentration). Several soil samples were collected from different depths on the measurement points to determine other parameters correlating to Rn and Tn concentrations in soil, like soil density and soil porosity as well as uranium and thorium activity concentrations.

In addition, a code for diffusion-advective radon transport, named RnMod3d developed by RISO, Denmark was applied for calculation of expected indoor radon[5].

４．研究成果

Faults lineament

At TA site, point 1, the soil penetrometer tests show that the surface soil is underplayed by coarser gravel material within 30 cm, creating an aeration zone mounted with a finer-texture impermeable soil. Ground penetrating radar survey has confirmed the concentration of clay and wetter soil in the lower-mid-transect. At TA site, point 2, the GPR transects revealed a depression in the ground that was filled, and an inconsistency of the ground layers between 45 and 60 m distance. Although the stream associated with the fault movement was defined as the survey location, it is most likely that lateral erosion has displaced the present scarp and the stream location, so that determining the exact location of the fault mirror was a complex task. Based on the GPR data (Figure 3), lateral movement is likely to have occurred.

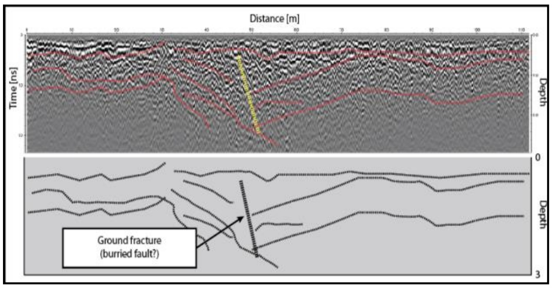


Figure 3. Ground penetrating radar TA survey results

In contrast to the faults in Takayama, where “constant” pressure is being applied, the research team attempted to determine whether Rn and Tn gas was also in high-concentration at a “passive” fault. The Ground Penetrating Radar data at Unzen Volcano penetrates the subsurface to a deeper depth (less moisture and clay). The material shows the Heisei eruption deposits over older fractured material, from which potential radon-thoron movement was pre-supposed (Figure 4).

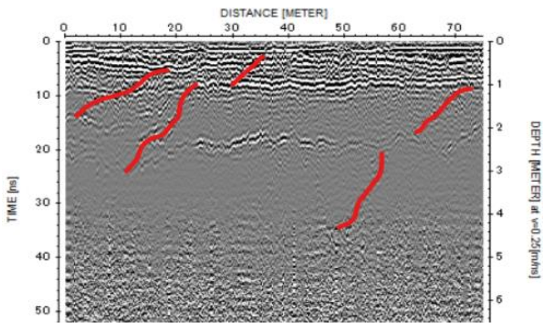


Figure 4. Subsurface starting from the fault scarp at Unzen Volcano (UD), with the main vertical ruptures (in red) showing fractures in the material. The top 1 m is made of the 1990-1995 eruption material deposits (fine ash subhorizontal layers).

Rn, Tn and environmental data

The results of the study are summarized in

Table 1. The values of Rn concentration in soil gas at UD site ranged from 1.8 to 5.7 kBq m^{-3} with a mean value of 4.1 kBq m^{-3}. Tn concentration was almost 5 times higher

than that of Rn with a mean value of 24.7 kBq m^{-3} with a range of 18 - 31 kBq m^{-3}. CO_2 concentration varied from 0.65 to 1.32% with a mean of 1.0%.

Table 1. Summary table of measurement results, results are presented as range for each parameter, i.e. min-max, with average value in parentheses[4].

Parameter	TA1	UD	CT
Rn [kBq m^{-3}]	1.1 – 74 (19)	1.8 – 5.7 (4.1)	8.4 – 14 (12)
Tn [kBq m^{-3}]	1.1 – 39 (18)	18.0 – 31 (24.7)	ND – 0.09 (0.03)
CO_2 [%]	0.4 – 6.2 (2.8)	0.65 – 1.32 (1.0)	2 – 3 (2.6)
k [μm^2]	0.2 – 39 (15)	1.1 – 2.3 (1.9)	0.3 – 23 (11.9)
U [Bq kg^{-1}]	17 – 36 (22)	15 – 17 (16)	26 – 35 (32)
Th [Bq kg^{-1}]	0.8 – 31 (18)	18 – 21 (20)	0.8 – 18 (13)
Exh [Bqm^{-2}h^{-1}]	25 – 95 (54)	13	57

Measured values (exept Tn and Th) at site TA1 were higher than at point UD. Rn concentration ranged from 1.1 to 74 kBq m^{-3} with a mean value of 19 kBq m^{-3} and the highest value (74 kBq m^{-3}) occurring on the potential fault. The variation of Tn concentration was much higher than at the UD site, ranging from 1.1 to 39 kBq m^{-3}, with the highest value on the fault. In addition, the peak of CO_2 concentration was also observed at points located on the fault.

At the CT point, the Tn concentration was very low. In contrast, U activity concentration was the highest.

In order to identify the outliers, i.e. possible location of the fault, the simple statistical technique based on ±2SD (standard deviation) was applied. It can be observed that on the UD site the Rn concentration varies with distance from the fault, without a significant increase and all the points are in the range between ±2SD (Figure 5a). In summary, fault identification is difficult.

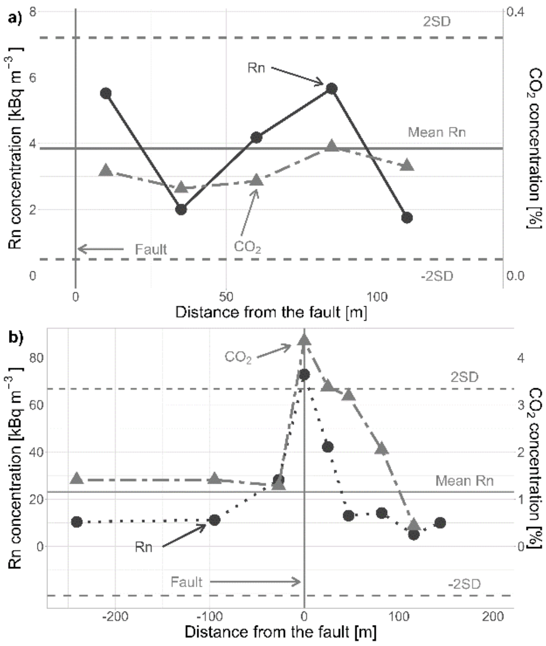


Figure 5. Rn concentration and CO2 in soil gas vs. distance from the fault: a) UD site, b) TA1 site

In contrast, at the TA1 site, a significant increase, above threshold of ±2SD, in the concentration of Rn and CO_2 was observed in the vicinity of the potential geological fault, as presented in Figure 5b. In addition, the positive correlation between Rn and CO_2 can be observed, especially on the TA1 site. It can be suggested that radon can be transported from the deeper layer by carried gas (i.e. CO_2). It also confirms the existence of high permeability, what in consequence suggests cracked soil structure.

GRP assessment

Geogenic (soil) radon is typically quantified by the GRP (Geogenic Radon Potential), a local measure that characterizes the susceptibility of a location to geogenic radon infiltration and which quantifies the radon emission potential as "what the earth delivers"[5]. The graphical representation of GRP in the relationship between Rn concentration and permeability with distinguish between Low/Medium/High Radon

Index (RI) zones is adapted from Neznal et al[6]. Results from Rn soil measurement and permeability were employed to assess the GRP as presented in Figure 6. Following the Czech approach, most measured points fall into Low or Medium RI zones. It can be observed that two points from the TA1 site are at High RI, and another two are at the border of Medium and High RI. These results were expected given the geological characteristics and the presence of an active fault. Three points from the CT site, which is characterized by Kanto loam formations, fall into the Medium RI zone primarily due to high permeability values. These results clearly demonstrate that points with the same radon concentration, but varying permeability levels can correspond to different radon risk levels. Consequently, the GRP is an excellent tool for decision-making, allowing for the exclusion of the potential presence of elevated indoor radon levels caused by the surrounding soils and geological environment of a house.

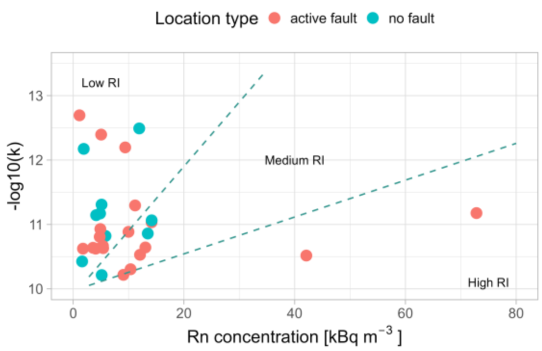


Figure 6. GRP assessment

Modelling of expected indoor Rn

The collected data was used as input for indoor radon modeling to better understand the importance of the various factors influencing combined diffusive and advective transfer. Two Japanese houses (traditional "T" and modern "M") with several scenarios (variation of measured parameters) were modelled. The difference between "T" and "M" are mainly based on the foundation type. In the "T" case air is the isolation between ground soil and the floor, whereas in the "M" case the concrete plate and anti-moisture insulation is considered. As presented in Figure 7 in the case of UD site there is almost no difference between expected indoor radon concentration in function of soil radon for traditional and modern type of house, what suggest that the soil characteristic is responsible for radon transport. On the other hand, for TA site, the type of isolation material is the main factor for advection-diffusion radon transport and finally indoor radon level.

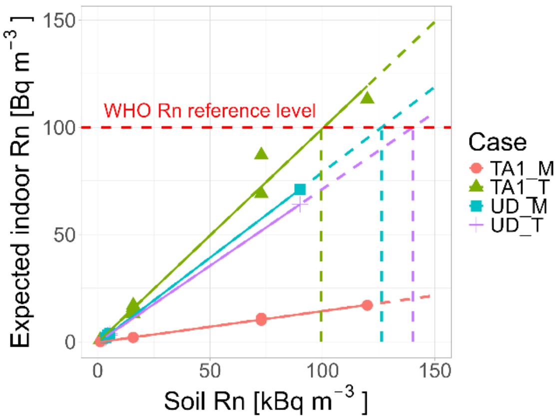


Figure 7. Modelling and calculation

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５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　1件／うちオープンアクセス　0件）

１．著者名 Miroslaw Janik, Christopher Gomez, Satoshi Kodaira, Md. Mahamudul Hasan	４．巻 NA
２．論文標題 PRELIMINARY RESULTS OF SPATIAL DISTRIBUTION OF RADON AND THORON WITH ASSOCIATED PARAMETERS IN SOIL AROUND ACTIVE FAULTS IN JAPAN	５．発行年 2024年
３．雑誌名 Radiation Protection Dosimetry	６．最初と最後の頁 NA
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/rpd/ncae117	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計3件（うち招待講演　0件／うち国際学会　0件）

１．発表者名 Miroslaw Janik
２．発表標題 Radon regulation and research in Asian-Pacific regio - is it possible to adopt European strategy?
３．学会等名 4th International Conference RADON IN THE ENVIRONMENT 2023
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１．発表者名 Miroslaw Janik
２．発表標題 Preliminary results of spatial distribution of radon and thoron with associated parameters in soil around active faults in Japan
３．学会等名 International Symposium on Natural and Artificial Radiation Exposures and Radiological Protection Studies (NARE2023)
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１．発表者名 Miroslaw Janik
２．発表標題 Soil as a source of indoor radon: from generation to indoor exposure
３．学会等名 GeoRad workshop
４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

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7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関