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**222Rn and 220Rn concentrations in soil gas of the Izera Massif (Sudetes, Poland) as a function of sampling depth**

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This research presents soil gas 222Rn and 220Rn concentrations measured at 17 locations in the Izera Massif of southwest Poland. The average 222Rn concentrations at sampling depths of 10, 40 and 80 cm were 8, 78 and 224 kBq m\(^{-3}\), respectively. The average 222Rn concentrations for the same depths (10, 40 and 80 cm) were 6, 10 and 13 kBq m\(^{-3}\), respectively. Profiles of the concentrations versus depth can be fitted by exponential, linear and polynomial functions for soils developed on fault zones, above uranium mineral deposits, and above faulted uranium deposits, respectively. Soils developed on bedrock without fault zones or uranium mineralisation exhibit concentrations that follow a power function with an exponent of p < 1.

Key words: radon and thoron, fault zones, uranium mineralisation, Izera Massif.

**INTRODUCTION**

The Izera Massif is located in the Sudetic Block (southeastern Poland; Fig. 1) and is part of the Izera-Karkonosze Massif. The central part of the Izera-Karkonosze Massif consists of the Variscan-aged Karkonosze granite pluton (Karkonosze Massif, Fig. 1) while surrounding areas are composed of older metamorphic rocks. The Izera Massif forms the northern envelope of the Karkonosze granite pluton. The massif records extensive lateral evidence of both thermal and metasomatic contact metamorphism. The Intra-Sudetic Fault Zone runs along the northern border of the Izera Massif. To the west, the Izera Massif borders the neighbouring Lusatian Fault Zone.

The radon isotopes 222Rn (referred to as “radon”, T\(_{1/2}\) = 3.82 d) and 220Rn (referred to as “thoron”, T\(_{1/2}\) = 55.6 s) belong to the 238U and 232Th decay series and occur as inert, radioactive gases. The mechanism by which 222Rn and 220Rn diffuse from minerals, soil and other regolith is not fully understood (Neznan et al., 1996; Ishimori et al., 2013; Malczewski and Dziurowicz, 2015). Atmospheric 222Rn concentrations normally range from 4 to 19 Bq m\(^{-3}\), whereas soil 222Rn concentrations vary between ~4 and 40 kBq m\(^{-3}\) (Eisenbud and Gesell, 1997).

Malczewski and Zaba (2007) presented a comprehensive survey of radon and thoron concentrations in soil gas of the Izera-Karkonosze Massif. The present contribution reports and interprets the relationship between Rn isotope concentrations and sampling depths within soils developed in association with fault zones and uranium mineralisation. This paper also compares 222Rn concentrations measured at 80 cm depth with results obtained by previous studies of the Izera Massif (e.g., Wołkowicz, 2007).

**GEOLOGICAL SETTING**

The Izera Massif consists mainly of gneisses, granite-gneisses, granites, granodiorites, leucogneisses, leucogranites and mica schists. Hornfelses, lephtites, gneisens, skarns, erlans, amphibolites, quartzites and quartz veins are rare but present. The Izera granites were emplaced by Early Paleozoic (Cambrian to Ordovician) magmatism. The granites, granodiorites and gneiss-es from the eastern part of the Izera Massif have been dated using several different methods and span a general age range of 550–460 Ma (Borkowska et al., 1980; Jarmotowicz-Szulc, 1984; Korytowski et al., 1993; Kröner et al., 2001).

The Izera gneisses are thought to be a polygenetic group. Most were formed by deformation of the Izera granite (Oberc-Dziedzic et al., 2005). The orthogneisses are mainly flaser gneisses and flaser-augen gneisses. Their deformation occurred over multiple episodes from the Early Paleozoic to the Pennsylvanian. A subset of gneisses including laminated gneisses or laminated augen gneisses probably reflects metamorphism of Neoproterozoic supracrustal series (Zaba, 1984). The protoliths were Neoproterozoic pelites such as clay rocks and mudstones. Mica-schists (supracrustal series) envelop the intrusive Izera granites (Oberc-Dziedzic et al., 2005) and form four parallel belts (Fig. 1). Mica-schists were metamorphosed at greenstone or amphibolite facies (Zaba, 1985; Cook and Dudek, 1994). Mica-schists from the Szklarska Poreba belt and from part of the Stara Kamienna belt have been metamorphosed to cordierite-andalusite-biotite hornfelses.

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The Izera Massif formations experienced several episodes of deformation (Zaba and Teper, 1989; Miezewski and Oberc-Dziedzic, 1990; Mazur and Kryza, 1998). The Izera Massif is cut by numerous faults running E–W, NW–SE, N–S and NE–SW (Fig. 1). The oldest E–W-trending faults frequently formed in association with the schist belts and generally run parallel to them. Multiphase fault-related activity and associated metasomatic processes (Smulikowski, 1972; Kozlowski, 1974; Žaba, 1984) resulted in the formation of leucogneisses, leucogranites and lephtinites (Fig. 1). Metasomatic processes have produced several different varieties of greisen (Fig. 1), which commonly exhibit ore-bearing mineralisation. Polymetallic mineralisation also occurs within the Stara Kamienna schist belt (Cook and Dudek, 1994; Mochnacka et al., 1995). Uranium and thorium mineralisation occurs throughout the Izera Massif (Mochnacka and Banaś, 2000). The soil gas measurements were carried out in sniff mode. In this mode, the built-in pump runs continuously and 222Rn and 220Rn concentrations are calculated from the data in electronic windows A and B, respectively. The cycle time was 15 min and three cycles were performed for all measurements. An average of these three cycles provided results reported for a given depth. Before each measurement, the RAD7 was purged for at least 10 min, or longer if the previous analysis detected high radon and thoron concentrations. Figure 3 shows sampling locations described in Table 1.

RESULTS AND DISCUSSION

Tables 2 through 5 report parameters derived from fitting 222Rn and 220Rn data to sampling depths. All of the fitting parameters are valid for sampling depths in the range of 10 to 80 cm.

MATERIALS AND METHODS

Measurements of soil 222Rn and 220Rn concentrations were performed using a RAD7 portable radon analysis system (Fig. 2). The detector operates with a sensitivity of 4 Bq m⁻³ and an upper linear detection limit of 800 kBq m⁻³. The upper range can be increased using a peripheral device. After inserting the stainless steel probe at the specified sampling depth (10, 40 and 80 cm), the sampling outlet was connected to the inlet of the RAD7 via a drying tube.

Fig. 1. Geological map of the Izera Massif area, showing measurement locations

1–17 – locations of in situ measurements

Fig. 2. The 16, 46 and 100 cm gas probes and RAD7 detector
$^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentrations in soil gas of the Izera Massif (Sudetes, Poland)...

Fig. 3. Photos of radon and thoron sampling locations

A – location 1 (Radoniów), B – location 2 (Proszówka), C – location 3 (Proszówka – Gryf Castle), D – location 4 (Mroczykowice), E – location 5 (Pobiedna), F – location 6 (Pobiedna), G – location 7 (Gierczyn), H – location 8 (Kotlina), I – location 9 (Opaleniec Mt.), J – location 10 (Świeradów Zdrój – SE area), K – location 11 (Izerski Stóg Mt.), L – locations 12 and 13 (Wojcieszycyz), M – location 14 (Rozdroże Izerskie), N – location 15 (Szklarska Poręba Dolna – Miśzys Las), O – location 16 (Szklarska Poręba Dolna – Zbójniska Skały), P – location 17 (Szklarska Poręba Średnia)
**Table 1**

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Rocks</th>
<th>Tectonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Radoniów – closed uranium mine</td>
<td>Fine-grained augen gneisses with granite-gneisses, leucogneisses, leucogranites, leptinites, mica-schists and amphibolites</td>
<td>NE–SW-trending fault nearby</td>
</tr>
<tr>
<td>2.</td>
<td>Prószówka</td>
<td>Augen gneisses</td>
<td>NE–SW-trending fault nearby</td>
</tr>
<tr>
<td>3.</td>
<td>Prószówka – Gryf Castle</td>
<td>Contact between Cenozoic basalts and augen gneisses</td>
<td>Volcanic features in the area follow a NE–SW-trending fault zone</td>
</tr>
<tr>
<td>4.</td>
<td>Mroczkowice near Mirsk – Okrągły Staw</td>
<td>Greisens</td>
<td>WNW–ESE-trending fault zone running parallel along the northern border of the Mirsk schist belt</td>
</tr>
<tr>
<td>5.</td>
<td>Pobiedna – closed uranium mine</td>
<td>Augen gneisses with symptoms of greisenization</td>
<td>Fault zones trending N–S and NE–SW, creating a distinct tectonic loop in the area</td>
</tr>
<tr>
<td>6.</td>
<td>Pobiedna – old uranium prospecting drift</td>
<td>Augen gneisses and granite-gneisses</td>
<td>Region cut by a NE–SW-trending fault zone</td>
</tr>
<tr>
<td>7.</td>
<td>Gierczyn – Blizbor Hill</td>
<td>Mica-schists (ore-bearing mineralisation)</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Kotlina</td>
<td>Leptinites</td>
<td>The leptinites follow an old E–W-trending fault zone, running along the southern border of the Stara Kamienna schist belt</td>
</tr>
<tr>
<td>9.</td>
<td>Świeradów Zdrój (Czerniawa) – Opaleniec Mt.</td>
<td>Leucogranites</td>
<td>Units near two fault zones: an older E–W-trending fault zone along the southern border of the Stara Kamienna schist belt and a slightly younger N–S-trending fault zone</td>
</tr>
<tr>
<td>10.</td>
<td>Świeradów Zdrój – SE area</td>
<td>Laminated augen gneisses</td>
<td>Gneisses occur at the intersection of a WNW–ESE-trending fault and a slightly younger NE–SW fault zone</td>
</tr>
<tr>
<td>11.</td>
<td>Izerkski Stóg Mt.</td>
<td>Fine-grained flaser-augen gneisses</td>
<td>Area cut by a distinct N–S fault zone</td>
</tr>
<tr>
<td>12.</td>
<td>Wojcieszyce – closed uranium mine</td>
<td>Augen gneisses and granite-gneisses</td>
<td>Contact zone of the Variscan Karkonosze granites</td>
</tr>
<tr>
<td>13.</td>
<td>Wojcieszyce – closed uranium mine</td>
<td>Augen gneisses</td>
<td>Contact zone of the Variscan Karkonosze granites</td>
</tr>
<tr>
<td>14.</td>
<td>Rozdroże Izerskie – closed quarry</td>
<td>Quartz vein</td>
<td>The fault zone runs NE–SW, zone cut by numerous younger, transverse, NW–SE trending faults</td>
</tr>
<tr>
<td>15.</td>
<td>Szkłarska Poręba Dolna – Mniszy Las</td>
<td>Hornfelses</td>
<td>Contact zone of the Variscan Karkonosze granites</td>
</tr>
<tr>
<td>16.</td>
<td>Szkłarska Poręba Dolna – Zbojeckie Škály</td>
<td>Hornfelses</td>
<td>Contact zone of the Variscan Karkonosze granites</td>
</tr>
<tr>
<td>17.</td>
<td>Szkłarska Poręba Średnia</td>
<td>Hornfelses</td>
<td>Contact zone of the Variscan Karkonosze granites</td>
</tr>
</tbody>
</table>

**Table 2**

Fitted parameters for the exponential function given by Eq. [1] (see text)

<table>
<thead>
<tr>
<th>Location</th>
<th>$^{222}$Rn</th>
<th>$^{220}$Rn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{222}$Rn</td>
<td>$^{220}$Rn</td>
</tr>
<tr>
<td>A</td>
<td>b</td>
<td>C$_{20}$ (kBq m$^{-3}$)</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>0.123</td>
</tr>
<tr>
<td>10</td>
<td>149</td>
<td>0.087</td>
</tr>
<tr>
<td>11</td>
<td>182</td>
<td>0.092</td>
</tr>
<tr>
<td>Location</td>
<td>$^{220}$Rn</td>
<td>$^{220}$Rn</td>
</tr>
<tr>
<td></td>
<td>$^{222}$Rn</td>
<td>$^{220}$Rn</td>
</tr>
<tr>
<td>9</td>
<td>0.581</td>
<td>0.135</td>
</tr>
<tr>
<td>11</td>
<td>653</td>
<td>0.043</td>
</tr>
</tbody>
</table>

Uncertainties estimated for parameters are ≤10%; $C_{20}$ refers to the average activity concentrations of $^{222}$Rn and $^{220}$Rn at 80 cm depth

**CONCENTRATIONS OF $^{222}$Rn AND $^{220}$Rn IN SOILS DEVELOPED WITHIN FAULT ZONES**

Sampling points located within fault zones (locations 9–11) showed exponential dependence of $^{222}$Rn on sampling depth (Fig. 4). The same pattern was also observed for $^{220}$Rn at locations 9 and 11 (Fig. 4). Concentration vs. depth profiles can be described by the exponential function:

$$C_{222/220}(\text{Bq m}^{-3}) = A \exp (b \cdot d)$$  \[1\]

where: d is the depth (cm).

Table 2 lists calculated values for A, b and the $^{222}$Rn and $^{220}$Rn concentrations at a depth of 80 cm. Concentrations of $^{222}$Rn at location 10 do not adhere to Eq. [1] because the sample location occurred on a steep slope. For slope sample locations, $^{220}$Rn concentration showed a pronounced inverse relationship with depth whereby the concentration significantly decreased with increasing depth (Malczewski and Zaba, 2007). As shown in Table 2, location 9 (Opaleniec Mt.) gave the highest b term values for both $^{222}$Rn and $^{220}$Rn (0.123 and 0.135, respectively). The highest $^{222}$Rn concentration (282 kBq m$^{-3}$) was recorded at location 11, whereas the highest $^{220}$Rn concentration (29 kBq m$^{-3}$) was recorded at location 9 (Table 2). Enhanced radon flux has been interpreted as an indicator of active fault zones since the 1970s. King (1978) reported an exponential trend of radon concentration vs. depth on the San Andreas Fault.

Neznał et al. (1996) reported the highest values of $^{222}$Rn concentrations among the sampling points, reaching 100–120 kBq m$^{-3}$. These values occurred in soils at a depth of 80 cm at locations in the test area (Chaby area, Prague, the
Lower 222Rn and 220Rn soil gas concentrations than those presented here were reported by Al-Hamidawi et al. (2012) in the vicinity of Al-Kufa city (Iraq), which is cut by fault zones located in sandstones. They observed average 222Rn concentrations of 3630, 4411 and 4717 Bq m⁻³, and the 220Rn concentrations of 13, 65, and 84 Bq m⁻³ at sampling depths of 50, 100 and 150 cm, respectively. Similar low values in the range of 29 to 7059 Bq m⁻³ at 50 cm depth were reported for soil radon measurements around fault lines in the western part of the north Anatolian fault zone (Turkey) by Yakut et al. (2017).

CONCENTRATIONS OF 222Rn AND 220Rn IN SOILS DEVELOPED ABOVE URANIUM DEPOSITS WITHOUT FAULT ZONES

Locations 1 and 12 represent known uranium deposits and exhibited linear relationships between 222Rn concentrations and soil depth (Fig. 5). Location 1 also showed linear 222Rn vs. depth relations (Fig. 5). This indicates that thorium follows a distribution similar to that of uranium at location 1. The 222Rn concentration vs. depth relation at locations 1 and 12, and 220Rn concentrations vs. depth at location 1 can be fitted by the linear expression:

$$C_{222\text{Rn}}(\text{Bq m}^{-3}) = A + (b \cdot d)$$  \[2\]

Table 3 lists calculated values for A and b along with 222Rn and 220Rn concentrations at 80 cm depth. As with location 10, location 12 also occurred along a slope and exhibited inverse 222Rn concentration vs. depth relations. Similar 222Rn concentration values at depths of 10, 40 and 80 cm from location 12 likely reflect interactions between inverse and linear influences on 220Rn concentrations (Fig. 5).
Fig. 5. $^{222}\text{Rn}$ (red circles) and $^{220}\text{Rn}$ (blue circles) concentrations vs. sampling depth at measurement points located above uranium deposits.

Solid lines represent linear regressions – Eq. [2]: R – correlation coefficient

CONCENTRATIONS OF $^{222}\text{Rn}$ AND $^{220}\text{Rn}$ IN SOILS DEVELOPED ABOVE FAULT ZONES WITH URANIUM MINERALISATION

Locations 5 and 6 (600 m apart) were located in Pobiedna amid both fault zones and uranium deposits. At these sites, $^{222}\text{Rn}$ concentration vs. depth measurements can be fitted by a second order polynomial function (Fig. 6):

$$C_{222} (\text{Bq m}^{-3}) = A + (b_1 \cdot d) + (b_2 \cdot d^2) \quad [3]$$

Table 4 lists calculated values for $A$, $b_1$, $b_2$ and the $^{222}\text{Rn}$ concentrations at 80 cm depth. As shown in Table 4, location 6 provided the highest $^{222}\text{Rn}$ concentration (~2.2 MBq m$^{-3}$) observed in the Izera Massif. The highest soil gas $^{222}\text{Rn}$ concentration was also recorded in Pobiedna (~7 MBq m$^{-3}$) during uranium ore prospecting activities from 1945–1954 (Soleczi, 1997). The observed deviation from linearity (Fig. 6) probably results from enhanced gas flow along fault zones in the area (Malczewski and Żaba, 2007). Location 5 exhibited a similar polynomial depth dependence of $^{220}\text{Rn}$ (Fig. 6 and Table 4). Because the RAD7 counts became non-linear at 80 cm depth, the exact $^{220}\text{Rn}$ concentration at location 6 could not be determined.

Goodwin et al. (2008) measured soil gas $^{222}\text{Rn}$ concentrations that ranged from 0.1 to 207 kBq m$^{-3}$ with a mean of 25 kBq m$^{-3}$ at a depth of 60 cm. These values were obtained from 72 sampling points in Nova Scotia (Canada). Nova Scotia is characterized by areas of elevated background levels and occurrences of uranium. The same authors reported soil gas radon concentrations of 500 to 1500 kBq m$^{-3}$ that were associated with the well-known Milet Brook uranium deposit. These values are similar to those presented here at locations 1 (Radoniów) and 6 (Pobiedna).

Table 3

<table>
<thead>
<tr>
<th>Location</th>
<th>$^{222}\text{Rn}$</th>
<th>$^{220}\text{Rn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A$</td>
<td>$b$</td>
</tr>
<tr>
<td>1</td>
<td>11981</td>
<td>5126</td>
</tr>
<tr>
<td>12</td>
<td>−10552</td>
<td>1827</td>
</tr>
<tr>
<td>Location</td>
<td>$^{220}\text{Rn}$</td>
<td>$^{222}\text{Rn}$</td>
</tr>
<tr>
<td>1</td>
<td>998</td>
<td>166</td>
</tr>
</tbody>
</table>

Uncertainties estimated for the parameters are ≤10%. $C_{av}$ refers to the average activity concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ at 80 cm depth.

In typical soils (without fault zones and/or uranium mineralisation) both the $^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentrations vs. depth follow a power function:
222Rn and 220Rn concentrations in soil gas of the Izera Massif (Sudetes, Poland)

Fig. 6. 222Rn (red circles) and 220Rn (blue circles) concentrations vs. sampling depth at measurement points located above uranium deposits and fault zones.

Table 4

<table>
<thead>
<tr>
<th>Location</th>
<th>222Rn</th>
<th>220Rn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>b1</td>
</tr>
<tr>
<td>5</td>
<td>-202647</td>
<td>20149</td>
</tr>
<tr>
<td>6</td>
<td>-17604</td>
<td>1676</td>
</tr>
</tbody>
</table>

Table 5

<table>
<thead>
<tr>
<th>Location</th>
<th>222Rn</th>
<th>220Rn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>p</td>
</tr>
<tr>
<td>4</td>
<td>2140</td>
<td>0.856</td>
</tr>
<tr>
<td>15</td>
<td>1798</td>
<td>0.640</td>
</tr>
</tbody>
</table>

Fitted parameters for the polynomial function given by Eq. [3] (see text)

Fitted parameters for the power function given by Eq. [4] (see text)

Uncertainties estimated for the parameters are ≤10%. C_{0i} refers to the average activity concentrations of 222Rn and 220Rn at 80 cm depth.

\[ C_{222/220} (\text{Bq} \, \text{m}^{-3}) = A \times d^p \]  

[4]

with the exponent \( p < 1 \) (Table 5). Figure 7 shows depth concentrations of 222Rn and 220Rn in soils developed on greisens (location 4) and hornfelses (location 15). As seen in Table 5, the calculated \( p \) value for 222Rn at location 4 is noticeably higher than that calculated for 220Rn. Location 15, however, gave comparable \( p \) values (within uncertainties).

Wang et al. (2016) reported average 222Rn and 220Rn concentrations of 130 and 188 kBq m^{-3}, respectively, at a depth of 80 cm in soils developed on weathered granite (S China). These values exceeded those obtained in our work at locations 4 and 15. For selected sites in the investigated area, the authors showed an almost exact logarithmic increase of 222Rn concentrations with sampling depths from 20 to 160 cm at intervals of 20 cm. No rule was observed for the 220Rn concentrations (Wang et al., 2016). Almayahi et al. (2013) obtained radon and thoron concentrations at a depth of 50 cm in Northern Peninsular Malaysia that ranged from 134 Bq m^{-3} to 143 kBq m^{-3}, and 55 to 423 Bq m^{-3}, respectively. The measurements were taken in soils mostly developed on granitic rocks, and the calculated average radon concentration was 29 kBq m^{-3} (Almayahi et al., 2013). Elzain (2017) has recently reported 222Rn concentrations ranging from 4.2 to 15.2 kBq m^{-3} with an average of 9.1 kBq m^{-3} in soils formed mainly on basaltic rocks in the eastern part of Sudan. In the paper, the 222Rn concentrations increased with sampling depth from 10 to 50 cm at intervals of 5 cm (Elzain, 2017).
Similar to the fault zones, considerably lower values of $^{222}\text{Rn}$ concentrations were reported for soils developed on sandstones (Hasan et al., 2011; Alharbi and Abbady, 2013). Hasan et al. (2011) presented soil gas $^{222}\text{Rn}$ concentrations of 788, 1490, 2128 and 3273 Bq m$^{-3}$ in the vicinity of Al-Najaf Al-Ashart city (Iraq) at depths of 5, 25, 35 and 60 cm, respectively. Alharbi and Abbady (2013) recorded average radon concentrations of 123, 163 and 220 Bq m$^{-3}$ in the Al-Quassim area (Saudi Arabia) at depths of 20, 40 and 60 cm, respectively.

Figures 8 and 9 compare $^{222}\text{Rn}$ concentrations at 80 cm obtained by Malczewski and Żaba (2007) with those reported by Wołkowicz (2007). As seen in Figure 8, Wołkowicz (2007) reported average $^{222}\text{Rn}$ values nearly three times lower than values presented here. This discrepancy likely reflects the elevated radon concentrations observed in fault zones. Wołkowicz

AVERAGE DEPTH CONCENTRATIONS OF $^{222}\text{Rn}$ AND $^{220}\text{Rn}$ IN SOILS FROM THE IZERA MASSIF

Fig. 7. $^{222}\text{Rn}$ (red circles) and $^{220}\text{Rn}$ (blue circles) concentrations vs. sampling depth at measurement points located in typical soils (without uranium deposits or fault zones)

Solid lines represent power function fits – Eq. [4]; $R^2$ – coefficient of determination

Fig. 8. Average $^{222}\text{Rn}$ (red bars) and $^{220}\text{Rn}$ (blue bars) concentrations of soil gas in the Izera Massif at specified depths

Fig. 9. Average $^{222}\text{Rn}$ (red bars) and $^{220}\text{Rn}$ (blue bars) concentrations of soil gas in the Izera Massif at specified depths


**REFERENCES**

Fig. 9. Comparison of average $^{222}$Rn concentrations at 80 cm depth calculated based on data reported by Wolkowicz (2007) and Malczewski and Zaba (2007)

Measurements by Wolkowicz (2007) avoided fault zones; standard deviations on the right-side graph are on the order of 20 kBq m$^{-3}$

(2007) avoided fault zones whereas this research did not. Results reported in Wolkowicz (2007) are consistent with those reported here, which were derived from locations without fault zones and uranium deposits (Fig. 9).

**CONCLUSIONS**

Results of $^{222}$Rn and $^{220}$Rn concentrations vs. depth in the Izera Massif have shown different patterns depending on the bedrock lithology, uranium mineralisation, and occurrence of fault zones. In soils developed above fault zones, a pronounced exponential relationship between $^{222}$Rn concentrations and depth was observed. This relationship may characterise active fault zones. Excluding fault zones and uranium deposits, the average $^{222}$Rn concentrations at 80 cm depth presented in this work resemble values reported for Izera Massif soils by previous research.

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