INTRODUCTION

The Izera Massif is located in the Sudetic Block (southwestern 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 Luzatian Massif.

The radon isotopes 222Rn (referred to as “radon”), T1/2 = 3.82 d and 220Rn (referred to as “thoron”, T1/2 = 56.6 s) belong to the 226U and 232Th decay series and occur as inert, radioactive gases. The mechanism by which 222Rn and 220Rn diffuses from minerals, soil and other regolith is not fully understood (Neznan et al., 1996; Ishimori et al., 2013; Malczewski and Dziurawicz, 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 aba (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., Wólkowicz, 2007).

GEOLOGICAL SETTING

The Izera Massif consists mainly of gneisses, granite-gneiss-es, granites, granodiorites, leucogneisses, leucogranites and mica schists. Hornfelses, leplinites, greisens, 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 gneisses 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; Jarmolowicz-Szulc, 1984; Korytowski et al., 1993; Kröner et al., 2001).

The Izera gneisses are thought to be a polygenic 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 (aba, 1984). The protoliths were Neoproterozoic petrites such as clay rocks and mudstones. Mica-schists (supracrustal series) envelope 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 (aba, 1985; Cook and Dudek, 1994). Mica-schists from the Śląskie Poręba belt and from part of the Stara Kamienna belt have been metamorphosed to cordierite-andalusite-biotite hornfelses.
The Izera Massif formations experienced several episodes of deformation (Zaba and Teper, 1989; Mierzejewski and Oberc-Dziedzic, 1990; Mazur and Kryza, 1996). 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; Koz³owski, 1974; Zaba, 1984) resulted in the formation of leucogneisses, leucogranites and leptinites (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 Kamiencica schist belt (Cook and Dudek, 1994; Mochnacka et al., 2015). Uranium and thorium mineralisation occurs throughout the Izera Massif (Mochnacka and Banañ, 2000).

**RESULTS AND DISCUSSION**

**MATERIALS AND METHODS**

Measurements of soil $^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentrations were performed using a RAD7 portable radon analysis system (Fig. 2). The detector operates with a sensitivity of 4 Bq m$^{-2}$ and an upper linear detection limit of 800 kBq m$^{-2}$. 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. 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 (Mroczkowice), 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 (Wojcieszycy), M – location 14 (Rozdroże Izerskie), N – location 15 (Szklarska Poręba Dolna – Mniszy Las), O – location 16 (Szklarska Poręba Dolna – Zbójeckie Skały), P – location 17 (Szklarska Poręba Średnia)
**Location of in situ measurements**

<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, lephtinites, mica-schists and amphibolites</td>
<td>NE–SW-trending fault nearby</td>
</tr>
<tr>
<td>2.</td>
<td>Proszówka</td>
<td>Augen gneisses</td>
<td>NE–SW-trending fault nearby</td>
</tr>
<tr>
<td>3.</td>
<td>Proszówka – 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 Mirk – Wyrwak Hill</td>
<td>Greisens</td>
<td>WNW–ESE-trending fault zone running parallel along the northern border of the Mirk schist belt</td>
</tr>
<tr>
<td>5.</td>
<td>Pobiedna – closed uranium mine</td>
<td>Augen gneisses with symptoms 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>Lephtinites</td>
<td>The lephtinites follow an old E–W-trending fault zone, running along the southern border of the Stara Kamienica 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 Kamienica 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>Izerski 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>Szkarska Poreba Dolna – Mniszy Las</td>
<td>Hornfelses</td>
<td>Contact zone of the Variscan Karkonosze granites</td>
</tr>
<tr>
<td>16.</td>
<td>Szkarska Poreba Dolna – Zbojeczki Skaly</td>
<td>Hornfelses</td>
<td>Contact zone of the Variscan Karkonosze granites</td>
</tr>
<tr>
<td>17.</td>
<td>Szkarska Poreba Średnia</td>
<td>Hornfelses</td>
<td>Contact zone of the Variscan Karkonosze granites</td>
</tr>
</tbody>
</table>

**Table 1**

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

<table>
<thead>
<tr>
<th>Location</th>
<th>$222\text{Rn}$</th>
<th>$222\text{Rn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A$</td>
<td>$b$</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>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>$220\text{Rn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A$</td>
</tr>
<tr>
<td>9</td>
<td>0.581</td>
</tr>
<tr>
<td>11</td>
<td>653</td>
</tr>
</tbody>
</table>

Uncertainties estimated for parameters are ≤10%; $C_{90}$ refers to the average activity concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ at 80 cm depth.

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

Table 2 lists calculated values for $A$, $b$, and the $^{222}\text{Rn}$ and $^{220}\text{Rn}$ concentrations at a depth of 80 cm. Concentrations of $^{222}\text{Rn}$ at location 10 do not adhere to Eq. [1] because the sample location occurred on a steep slope. For slope sample locations, $^{220}\text{Rn}$ concentration showed a pronounced inverse relationship with depth whereby the concentration significantly decreased with increasing depth (Malczewski and Żaba, 2007). As shown in Table 2, location 9 (Opaleniec Mt.) gave the highest b term values for both $^{222}\text{Rn}$ and $^{220}\text{Rn}$ ($0.123$ and $0.135$, respectively). The highest $^{222}\text{Rn}$ concentration (282 kBq m$^{-3}$) was recorded at location 11, whereas the highest $^{220}\text{Rn}$ 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.

Neznal et al. (1996) reported the highest values of $^{222}\text{Rn}$ 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
Czech Republic) where there are tectonic zones with transverse faults. Barnet and Pacherová (2015) recorded average values of $^{222}\text{Rn}$ concentrations that ranged from 12 to 22 kBq m$^{-3}$ and 18 to 60 kBq m$^{-3}$ in sites located in contact zones (granitoids or migmatites with sandstones, and trachytes with Cretaceous sediments; Klatovy, Kytlice, Veseli nad Lužnicí and Chrudim areas, the Czech Republic) at depths of 50 and 80 cm, respectively. Al-Tamimi and Abumurad (2001) reported the soil radon concentrations that ranged from 25 to 60 kBq m$^{-3}$ at 50 cm depth along faults in Wadi um Ghudram and Wadi Es-sir Formation (N Jordan).

Lower $^{222}\text{Rn}$ and $^{220}\text{Rn}$ 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 $^{222}\text{Rn}$ concentrations of 3630, 4411 and 4717 Bq m$^{-3}$, and the $^{220}\text{Rn}$ 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 $^{222}\text{Rn}$ AND $^{220}\text{Rn}$ IN SOILS DEVELOPED ABOVE URANIUM DEPOSITS WITHOUT FAULT ZONES

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

$$C_{222/220}(\text{Bq m}^{-3}) = A + (b \times d) \quad [2]$$

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

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

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 (Solecki, 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).

CONCENTRATIONS OF $^{222}\text{Rn}$ AND $^{220}\text{Rn}$ IN TYPICAL SOILS

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:

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

Wang et al. (2016) reported average $^{222}\text{Rn}$ and $^{220}\text{Rn}$ 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 $^{222}\text{Rn}$ concentrations with sampling depths from 20 to 160 cm at intervals of 20 cm. No rule was observed for the $^{220}\text{Rn}$ 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 $^{222}\text{Rn}$ 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 $^{222}\text{Rn}$ 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
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 222Rn and 220Rn 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 222Rn concentrations and depth was observed. This relationship may characterise active fault zones. Excluding fault zones and uranium deposits, the average 222Rn concentrations at 80 cm depth presented in this work resemble values reported for Izera Massif soils by previous research.

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