Using $^{222}\text{Rn}/^{220}\text{Rn}$ versus $^{226}\text{Ra}/^{232}\text{Th}$ activity ratio and CO$_2$ concentration in soil gas to trace advective fluxes

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**RESEARCH FOCUS**

Soil radon transport along fault systems where deep fluids uprise

**DISCRIMINATION OF SOIL RADON TRANSPORT**

- Measurement of soil gas concentrations of $^{222}\text{Rn}$ and $^{220}\text{Rn}$ at 80 cm depth;
- $^{222}\text{Rn}/^{220}\text{Rn}$ activity ratio ($t_{1/2}$ very different);
- Evaluation of seasonal soil $^{222}\text{Rn}$ fluctuations;
- $^{226}\text{Ra}$ and $^{232}\text{Th}$ contents in soil;
- $^{222}\text{Rn}/^{220}\text{Rn}$ versus $^{226}\text{Ra}/^{232}\text{Th}$ activity ratio;
- Measurement of soil CO$_2$ concentrations at 80 cm depth (main radon carrier gas);
- Determination of enrichment coefficient of radon;
SOIL RADON CONCENTRATION

- Geological subsurface nature (particle size, mineralogical composition, parent elements)
- Soil gas permeability
- Meteo-climatic parameters
- Presence of faults, fractures or deep fluid uprise

SOIL RADON TRANSPORT

**DIFFUSIVE**

\[ f = -D \cdot \frac{dc}{dz} \]

- \( f \) = diffusive flow intensity (cm³ cm⁻² s⁻¹);
- \( D \) = molecular diffusion coefficient (cm² s⁻¹);
- \( \frac{dc}{dz} \) = gas concentration change in the system (m³/m³) along a length \( dz \) (m).

**ADVECTIVE**

\[ v = k \cdot \frac{(-\Delta p + \gamma g)}{\mu} \]

- \( v \) = gas velocity (cm s⁻¹);
- \( k \) = permeability (m²);
- \( \Delta p \) = pressure variation along a vertical \( z \) (m);
- \( \mu \) = gas dynamic viscosity (kg m s⁻¹);
- \( \gamma g \) = gas density (kg m⁻³).

Radon source in the vicinity of the measurement point

Deep Radon source

\[ ^{222}\text{Rn} / ^{220}\text{Rn} \ll ^{226}\text{Ra} / ^{232}\text{Th} \]

\[ ^{222}\text{Rn} / ^{220}\text{Rn} > ^{226}\text{Ra} / ^{232}\text{Th} \]
GEOLOGICAL SETTING

SITE | GEOLOGICAL BEDROCK
--- | ---
Terme della Ficoncella | Travertines and Flysch sediments
Fiumicino | Pleistocene-Holocene sediments (Tiber Delta plain)
Vigna Fiorita | Lahar flows and ignimbrites of the Colli Albani Complex
Radon and thoron activity concentrations (at 80 cm depth): hollow probe (1) (Radon v.o.s. corp.) attached (2) to a drying unit (3) and to the continuous radon monitor (4) (RAD7 Durridge Co.), connected in series.
RESULTS FROM TERME DELLA FICONCELLA (CIVITAVECCHIA)

Travertine $^{226}\text{Ra}/^{232}\text{Th} = 6.14$

- Rich soil in $^{226}\text{Ra}$ and poor in $^{232}\text{Th}$;
- $^{226}\text{Ra}/^{232}\text{Th} = 6.14$
- $^{222}\text{Rn}/^{220}\text{Rn}$ activity ratio
- TFF1 and TFF2 permanent station
- TFF1: mean $\text{CO}_2$ - 1.6 vol.%;
- TFF2: mean $\text{CO}_2$ - 2.1 vol.%;
- TFF1 radon transport predominantly diffusive;
- TFF2 radon transport diffusive and advective;
SOIL GAS MEASUREMENTS ACROSS CIVITAVECCHIA FAULT

$^{226}\text{Ra}/^{232}\text{Th}$ Flysch = 1.13

Measures distance (m)

$^{226}\text{Ra}/^{232}\text{Th}$ Flysch = 1.13

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Measures distance (m)

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Measures distance (m)

$^{226}\text{Ra}/^{232}\text{Th}$ Flysch = 1.13

CO$_2$(vol.%)
Degassing of this area occurs at faults of the Ciampino carbonate high that acts as a reservoir for large quantities of gases (primarily composed of CO$_2$, H$_2$S and radon) deriving from deep residual magmatic activity. These gases represent a high risk of indoor gas accumulation for the inhabitants of the area.

\[ \frac{^{226}\text{Ra}}{^{232}\text{Th}} \text{ of Villa Doria Unit} = 0.54 \]

**RESULTS FROM VIGNA FIORITA (CIAMPINO)**

VF1 and VF2 permanent station
✓ significant differences in $^{222}$Rn and CO$_2$ concentrations and in the seasonal variability;

✓ VF1: mean CO$_2$ - 4.7 vol.%;
✓ VF2: mean CO$_2$ - 70.1 vol.%;

✓ VF1: radon transport diffusive and advective;
✓ VF2 radon transport strictly advective.
SOIL GAS MEASUREMENTS ACROSS VIGNA FIORITA FAULT

PROFILE 1:
8 measures, 180 m length, 20 m equidistance

PROFILE 2:
8 measures, 100 m length, 15 m equidistance

$^{226}\text{Ra}/^{232}\text{Th}$ $\tilde{n}$Tavolato Unit$\tilde{o}$ = 1.4

(Giordano et al., 2009)

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SOIL GAS MEASUREMENTS ACROSS VIGNA FIORITA FAULT

PROFILE 1:
8 measures, 180 m length, 20 m equidistance

PROFILE 2:
8 measures, 100 m length, 15 m equidistance

\(^{226}\text{Ra}/^{232}\text{Th} \sim \text{Tavolato Unit}= 1.4\)
SOIL GAS MEASUREMENTS PROFILES ACROSS VIGNA FIORITA FAULT

Location of profiles

AR1
AR2
AR3
AR4
AR5
AR6

226Ra/232Th ratio map

CO₂ concentration map

AR1
226Ra/232Th 1.4

AR3

AR5

AR2
226Ra/232Th 1.4

AR4

AR6

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In the Fiumicino area in August 2013, two boreholes at 35m depth, caused a gas blowout from a pressurized clay-confined gas pocket. Other past events of this type have also been reported in the area with gases mainly composed of CO$_2$ with traces of CH$_4$ and H$_2$S.

Soil gas measurements have been carried out on active pools in the roundabout (1) and on the adjacent area to the north (2, called circus land).
**222Rn/220Rn MAP VS CO₂ CONCENTRATION IN THE ROUNDABOUT**

### Parameter Statistics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>St. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}\text{Rn}$ ($\text{Bq/m}^3$)</td>
<td>6180</td>
<td>29150</td>
<td>11760</td>
<td>4070</td>
</tr>
<tr>
<td>$^{222}\text{Rn}/^{220}\text{Rn}$</td>
<td>0.05</td>
<td>1.04</td>
<td>0.27</td>
<td>0.24</td>
</tr>
<tr>
<td>$\text{CO}_2$ (vol.%)</td>
<td>1.6</td>
<td>88</td>
<td>25.9</td>
<td>25.65</td>
</tr>
</tbody>
</table>

Legend:
- **Main blowout**
- **Secondary blowout**
- Soil gas measure point with CO₂ value
Table 1: Parameter range and statistical values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>St. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}$Rn (Bq/m$^3$)</td>
<td>1200</td>
<td>5780</td>
<td>3690</td>
<td>1080</td>
</tr>
<tr>
<td>$^{222}$Rn/$^{220}$Rn</td>
<td>0.1</td>
<td>1.45</td>
<td>0.24</td>
<td>0.27</td>
</tr>
<tr>
<td>CO$_2$ (vol.%)</td>
<td>0.2</td>
<td>88</td>
<td>7.22</td>
<td>21.67</td>
</tr>
</tbody>
</table>

**222$^{Rn}$/220$^{Rn}$ MAP VS CO$_2$ CONCENTRATION IN THE CIRCUS LANDò**

Legend:
- Soil gas measure point with CO$_2$ value
- Main gas blowout
- Secondary gas blowout

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Radon transport mainly diffusive;

- some measuring points have diffusive and advective mechanism;
- theese measuring points are located near gas blowout.

Radon transport strictly diffusive;

- large disequilibrium between $^{226}\text{Ra}$ and $^{232}\text{Th}$ in the soil;
- in the three hotspots there is increase in the advective component where the highest soil CO$_2$ concentrations were recorded.
ASSESSMENT OF ENRICHMENT COEFFICIENT

Generally **Radon Emanation** is the number of atoms of radon leaving the solid material divided by the amount generated from the sample. Where values higher than 0.5 - 0.7 can be used to trace advective fluxes of deep gases (Schuman, 1993).

In this study, we also obtained values greater than 1, which is actually an indication of **Radon Enrichment**.

\[
E.C. = \frac{C_{222Rn}}{C_{226Ra} \cdot \rho}
\]

where:
- \( C_{222Rn} \) = soil radon activity concentration (Bq/m³);
- \( C_{226Ra} \) = soil \(^{226}\text{Ra} \) content (Bq/kg);
- \( \rho \) = soil density (kg/m³).

<table>
<thead>
<tr>
<th>ID measurements point</th>
<th>soil (^{222}\text{Rn} ) (Bq/m³)</th>
<th>(^{226}\text{Ra} ) (Bq/kg)</th>
<th>E.C. (( \rho ) 1200 kg/m³ soil density)</th>
<th>E.C. (( \rho ) 1400 kg/m³ soil density)</th>
<th>soil CO₂ (vol. %)</th>
<th>Soil Radon transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>VF1 Vigna fiorita*</td>
<td>72000</td>
<td>57.5</td>
<td>1.04</td>
<td>0.89</td>
<td>4.7</td>
<td>Diffusive-advective mixed</td>
</tr>
<tr>
<td><strong>VF2 Vigna fiorita</strong>*</td>
<td><strong>169880</strong></td>
<td><strong>43.0</strong></td>
<td><strong>3.29</strong></td>
<td><strong>2.82</strong></td>
<td><strong>70.1</strong></td>
<td><strong>Strictly advective</strong></td>
</tr>
<tr>
<td>TFF1 T. Ficoncella*</td>
<td>128000</td>
<td>91.8</td>
<td>1.18</td>
<td>1.00</td>
<td>1.6</td>
<td>Diffusive-advective mixed</td>
</tr>
<tr>
<td><strong>TFF2 Ficoncella</strong>*</td>
<td><strong>382270</strong></td>
<td><strong>224.1</strong></td>
<td><strong>1.42</strong></td>
<td><strong>1.22</strong></td>
<td><strong>2.1</strong></td>
<td><strong>Diffusive-advective mixed</strong></td>
</tr>
<tr>
<td>Roundabout MIN Fiu.</td>
<td>6180</td>
<td>28.1</td>
<td>0.18</td>
<td>0.15</td>
<td>1.6</td>
<td>Diffusive</td>
</tr>
<tr>
<td>Roundabout MAX Fiu.</td>
<td>29150</td>
<td>28.1</td>
<td>0.86</td>
<td>0.74</td>
<td>88</td>
<td>Diffusive-advective mixed</td>
</tr>
<tr>
<td>Circus (MIN) Fiu.</td>
<td>1200</td>
<td>31.4</td>
<td>0.03</td>
<td>0.03</td>
<td>0.2</td>
<td>Diffusive</td>
</tr>
<tr>
<td>Circus (MAX ) Fiu.</td>
<td>5780</td>
<td>31.4</td>
<td>0.15</td>
<td>0.13</td>
<td>88</td>
<td>Diffusive</td>
</tr>
</tbody>
</table>

*three years monitoring at permanent stations on a monthly basis

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CONCLUDING REMARKS

- Faults and fractures are preferential pathways for strictly advective $^{222}$Rn uprise from deep sources.

- Advective movement is favoured by the presence of the carrier gas (CO$_2$), capable of carrying the radon from deeper to more superficial areas.

- For the recognition of deep sources the signal given by the $^{220}$Rn is important, as the concentration tends to decrease significantly because of its low half-life.

- $^{222}$Rn/$^{220}$Rn ratio signal, together with the knowledge of the soil content of $^{232}$Th and $^{226}$Ra of a given area is a stronger signal than the soil $^{222}$Rn concentration on its own.

- Evaluation of both the soil gases and its intrinsic permeability are vital for the investigation of unconformities and for risk assessment of indoor environments.
Thank you for your attention