A guideline for the evaluation of the soil radon potential based on geogenic and anthropogenic parameters

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Abstract Following a brief review about radon (^{222}Rn) in soils, this study gives a compilation and evaluation of important parameters of the soil ^{222}Rn potential. Because investigations of the potential are usually limited to rural areas, anthropogenic or urban effects have not attracted much attention so far. Measurements within the densely populated Ruhr district (Germany) present some new insights into geogenic and anthropogenic parameters on the soil ^{222}Rn potential. According to their importance, seven parameters were strung in aranking system, which can be applied in both rural and urban areas: made grounds, geology, relief, vegetation cover, tectonics, soil sealing, traffic vibrations. While the first four parameters control the soil ^{222}Rn potential on a more regional scale, the last three can modify it locally. Furthermore, an evaluation of the potential within a ten-point-system is proposed. The advantage of the system lies in the possibility to estimate the soil ^{222}Rn potential of any site on a local scale. Common classifications and rankings, based on insufficiently scaled maps, can be included in the proposed system.

Keywords Emanation · Radon · Soil ^{222}Rn potential · Soil sealing · Traffic vibrations

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Introduction

The natural occurring radioactive noble gas ^{222}Rn and its solid decay products are responsible for about 50% of the natural radiation dose to the public. Until today, the radiological consequences of this exposure are still under discussion and range from "no risk verifiable" (Cohen 1998) to "most important natural risk factor for lung cancer" (Steindorf and others 1995).

^{222}Rn exposure of the public mainly takes place in buildings, where ^{222}Rn can accumulate. The most important source of indoor ^{222}Rn is the soil, whereas building material is usually negligible. ^{222}Rn transfer from the soil to the building depends on constructional features and usage peculiarities, which change from building to building and are hardly predictable. On the other hand, the occurrence and availability of ^{222}Rn in the soil (described by the term 'soil ^{222}Rn potential'), is more predictable, if the processes controlling this potential are sufficiently understood. Therefore, investigations about soil ^{222}Rn potential are conducted worldwide to clarify and quantify such processes. Unfortunately, most of the studies are limited to rural areas. Under natural and undisturbed soil conditions, geogenic and meteorological parameters on the distribution and availability of ^{222}Rn are explored in detail. However, within urban areas, such natural parameters can be modified by anthropogenic ones, so the determined ^{222}Rn potential of rural areas cannot be transferred to urban areas without problems.

Because cities represent small areas with a high population, it is important to record the ^{222}Rn potential as well as the soil ^{222}Rn potential of these densely populated areas as precisely as possible. At the moment, about half ofthe 80 million citizens of Germany live in densely populated areas, which make up 7% of the territory of the Federal Republic (Blume 1996). It is the first time that 50% of the worldwide population now lives in urban areas, which represent only 0.7% of the continental Earth's surface (Mulder 1995). If the growth of the cities should continue, the urban population will double by 2025 (POPIN 2000). This enumeration shows that it has become urgent to investigate the anthropogenic influences on environmental processes, which can especially dominate in urban areas over natural processes. In this sense, the soil ^{222}Rn potential of the Ruhr district (4,400 km^2, ~5.4 million people) was investigated – a region that stretches between the cities of Krefeld, Essen, Dortmund, Recklinghausen and

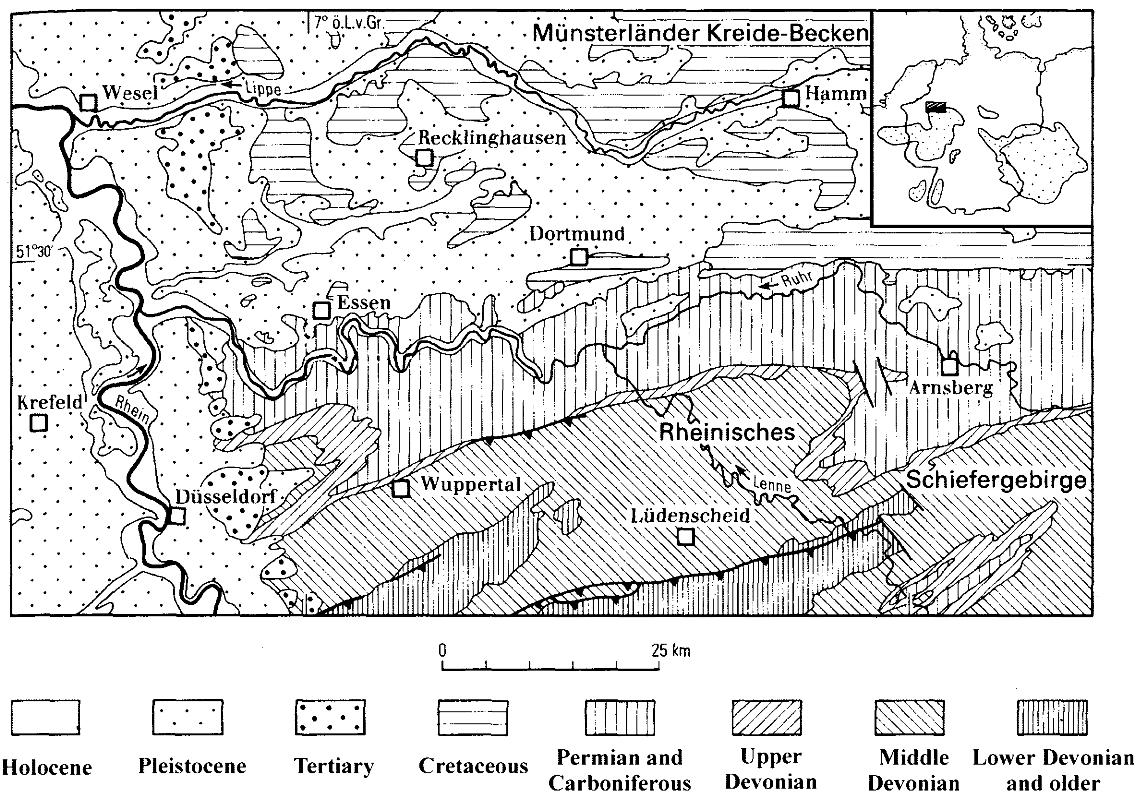
Wesel (Fig. 1), and probably represents the largest economic area and densely populated region within Europe.

Soil ^{222}Rn potential

Radon is a natural occurring radioactive noble gas with 32 isotopes. Only two of them, ^{222}Rn (radon) and ^{220}Rn (thoron), are of environmental importance. Especially ^{222}Rn, which is generated within the ^{238}U decay series, can reach the human environment, because of its relatively long half-life of 3.8 days (Fig. 2). ^{220}Rn is generated within the ^{232}Th decay series and has a half-life of 56 s.
The number of ^{222}Rn atoms, which is transferred from the soil to the atmosphere, is controlled by different lithological, physical soil and meteorological conditions. These can be pictured through three processes. The ^{222}Rn emanation describes the ^{222}Rn release from the solid phase of the soil (mineral grains, soil particles) to the pore or joint space. The movement of the released ^{222}Rn atoms through gas or water-filled voids is called ^{222}Rn migration, which can be a result of diffusive and/or convective processes. Finally, the ^{222}Rn exhalation describes the passage of ^{222}Rn from the soil into the atmosphere. All three processes – emanation, migration and exhalation – determine the soil ^{222}Rn potential (see electronic supplementary material).

Because the term ^{222}Rn potential is not used unequivocally, it is necessary to define it. Most often, a ^{222}Rn potential is understood as the probability that new or existing buildings will exceed a radon reference level (Gundersen and Schumann 1996; Miles and Ball 1996). Such classifications are based on geological data as well as indoor radon measurements. The same term is defined by the Austrian radon project (Friedmann and others 1996) as the annual mean radon concentration in a standard dwelling, wherebythis classification goes back to indoor radon measurements only. Another approach is to characterise the ^{222}Rn potential solely of the soil. The main advantage of this system is to separate the influences of the soil on the ^{222}Rn potential from those of building characteristics, because the latter can change quickly and are difficult to predict. This approach is followed by Kemski and others (1996b, 1999), who use soil gas ^{222}Rn concentrations and gas-permeabilities of the soils as parameters to classify geogenic radon potential. Following the definition of Kemski and others (1999), the term soil ^{222}Rn potential is introduced in this study. It should be distinguished from the former definition, because it also includes anthropogenic parameters. The term 'soil' is understood in the sense of regolith throughout the study. Usually, the process of exhalation remains unconsidered when investigating any ^{222}Rn potential, because exhalation is very sensitive to meteorological conditions and has no direct influence on ^{222}Rn concentrations in buildings. However, if the soil surface is sealed, the ^{222}Rn concentration of the soil gas rises because of a reduction in exhalation. Thus, the soil ^{222}Rn potential cannot be a result of a weighting of emanation and migration processes only,

Fig. 1
Geological sketch map of the investigated area (after Pieper 1990). *Inserted map* shows the border of Germany



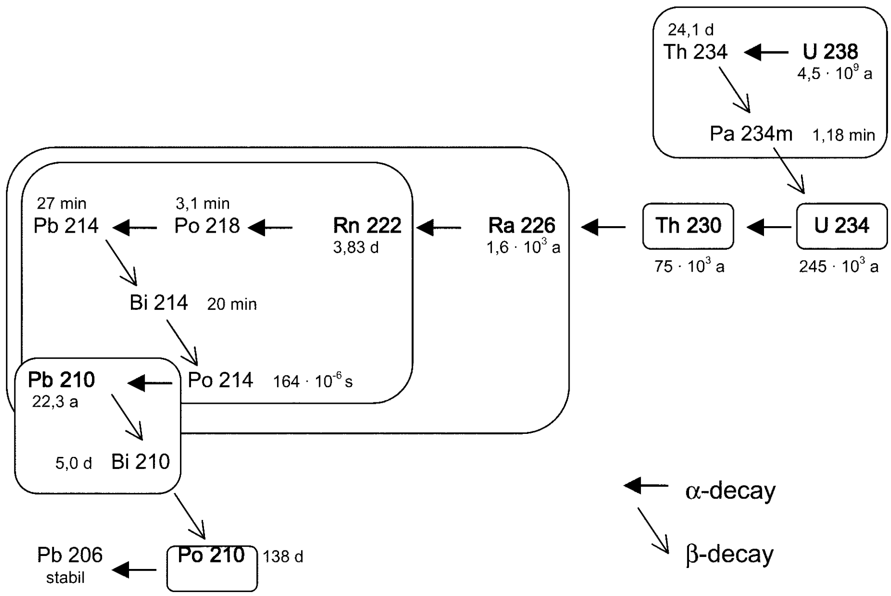


Fig. 2
Simplified ^{238}U decay series with half-lives (after Surbeck 1995)

but exhalation should be considered as well. The measurement of exhalation rate is the only possibility to receive information about the actual ^{222}Rn flux within or from the soil. For these reasons the term soil ^{222}Rn potential is understood in this study as a qualitative and semi-quantitative evaluation of emanation, migration and exhalation, and is finally ranked by values between 0 and 10.

Methods

For the determination of soil ^{222}Rn concentrations, soil gas was sampled from a depth of 0.8 m, and the samples were measured within Lucas cells (1957). The ^{222}Rn exhalation rates were determined by the accumulator method using stainless steel cylinders and Lucas cell measurements. Subsequent to the soil-gas sampling, the gas permeability of the soil was determined at the sampling depth by measuring the flow resistance. From selected soil samples, ^{226}Ra concentrations were measured γ-spectroscopically using a high-resolution HPGe detector (see electronic supplementary material, Description of applied methods).

Ranking of main parameters affecting the soil ^{222}Rn potential

Made ground

Probably the strongest parameter on the soil ^{222}Rn potential occurs through the substitution of natural soils through made grounds (backfill) with a thickness >2 m. This is especially important within urban areas, where made grounds are distributed widely. By substituting the natural soil, practically all geogenic parameters of the soil potential are changed totally. Therefore, the first question when estimating soil ^{222}Rn potential of a site should be, is this an undisturbed soil or a made ground? The composition of made grounds varies distinctly. According to their material, they can be differentiated into three main groups:

1. made ground representing a re-sorted soil (soil aggradation);
2. made ground, which consists of natural clastic, loose sediments (sand, gravel), rock debris (railroad embankment) or tailings (in this study from hard coal mining);
3. made ground from anthropogenic material such as rubble, slags and ashes, sludges and garbage.

Table 1 compiles the ^{222}Rn concentrations and exhalation rates of typical made ground types found in the Ruhr district. The values of the last two lines give the median values for all measurements conducted on made ground or undisturbed soil. Comparing only the values of the last two lines, it is obvious that the soil ^{222}Rn potential of a made ground is distinctly lower than that of undisturbed soil. The differences in ^{222}Rn concentrations are larger (9 vs 43 Bq/l: factor F=5) than the differences in exhalation rates [31 vs 61 Bq/(m^2/h): F=2]. This shows clearly that the emanation rate of a made ground is very small on average, and it underlines that most made grounds have higher gas permeabilities, resulting in relatively high exhalation rates. The low ^{222}Rn emanation rate is very typical for made grounds of type 2 (loose sediment and tailings in Table 1). Such materials are coarse grained, and the fraction of ^{226}Ra atoms on or close to mineral surfaces is small. Additionally, the content of soil moisture is low, which accounts for the low emanation rate as well.
Not surprisingly, the soil ^{222}Rn potential in soil aggradation is relatively similar to an undisturbed soil (Table 1). Nevertheless, it has a slightly lower potential than its undisturbed equivalent. Probably, the destroyed soil structure reduces not only the ^{222}Rn migration (small exhalation rate), but also reduces its subsequent delivery from depth as well (low concentration within soil gas).

Table 1
^{222}Rn concentrations (depth of 0.8 m) and exhalation rates of different types of made grounds. Given values are medians, and number of measurements are shown in parentheses

Type of made ground	^{222}Rn concentration of soil gas (Bq/l)	^{222}Rn exhalation rate [Bq/(m^2/h)]
Soil aggradation	30 (15)	46 (5)
Loose sediment, tailings	8 (172)	22 (13)
Rubble	33 (27)	80 (10)
Slags, ashes	92 (3)	
Sewage sludges	–	206 (1)
Median of made ground	9 (217)	31 (29)
Median of undisturbed turbed soil	43 (307)	61[a]

[a] Value from NCRP 1988)

Relatively high exhalation rates were observed on rubble (Table 1). At the investigated sites the material was a mixture of rubble and soil aggradation. Although the latter was responsible for emanation rates and ^{222}Rn concentrations were similar to a pure soil aggradation, the skeletal fraction of the rubble enhanced gas permeability, thus large exhalation rates could be measured.
Made ground materials with high soil ^{222}Rn potentials belong to the groups of slags and ashes, and sewage sludges (Table 1). Especially the former are distributed widely, but are seldom accessible because they are used as a filling material in road construction. The high ^{222}Rn concentrations are caused by high ^{226}Ra concentrations of the material, which range from 200–400 Bq/kg (own data), but can exceed 1,000 Bq/kg (BMU 1994). The very high exhalation rate of sewage sludge is a special feature of the Ruhr district, where pit waters with high ^{226}Ra concentrations (up to 32 Bq/l) are released to the rivers, resulting in high ^{226}Ra concentrations (up to 1,600 Bq/kg) of the sludge (Feige and Wiegand 1999). The increase in ^{222}Rn concentrations in soil gas between made grounds with high and low ^{226}Ra concentrations isabout F =10 (92 vs 9 Bq/l, Table 1). However, because of the small number of measurements of made grounds with high ^{226}Ra concentrations, this value should not be overestimated.
With respect to indoor ^{222}Rn concentrations, a made ground starts to be important, when its thickness exceeds the depth of the building foundation, i.e. this is ~2–3 m for common buildings with a cellar. Made grounds <2 m change the soil ^{222}Rn potential within the first 2 m, but do not significantly influence the ^{222}Rn entry rate into buildings with cellars. Therefore, it is recommended to investigate the soil ^{222}Rn potential at building plots at foundation depth. This is especially important for made grounds, but for many Quaternary covers such as loess or solifluction soils as well.

Variety of rocks

The second most important parameter of the soil ^{222}Rn potential is the type of bedrock beneath the soil. Nearly all studies investigating the soil ^{222}Rn potential made the observation that the geological situation is not the second, but the most important parameter (Gundersen and Szabo 1995; Kemski and others 1996b). This is true if there is no made ground thicker than 2 m. If there is, then the type of made ground is more important because of the limited migration distance of ^{222}Rn, which means that a ^{222}Rn signal from the bedrock at depth will not trace through a thick made ground.
It is obvious that the radionuclide concentration of rocks is one of the most important fundamental influences on soil ^{222}Rn potential. As a first approximation it can be described through the parameter 'variety of rocks'. In most cases, rocks with high ^{226}Ra concentrations develop soils with high ^{226}Ra concentrations; exceptions are described by Surbeck (1991) or Schumann and Gundersen (1996). Not only is the ^{238}U or ^{226}Ra concentration of a soil controlled by the type of bedrock, but the gas permeability of a soil, which determines the migration distance, depends on the bedrock as well.
Table 2 gives a compilation of ^{238}U concentrations of common rock groups. Comparing the average ^{238}U concentration of soils with that ofrocks shows that, because of weathering processes, radionuclides can be enriched within soils. This is especially true for limestones within the investigated area. Even if these rocks are poor in ^{226}Ra, high ^{226}Ra concentrations are observed within their soils. During the tropic conditions of the Tertiary period, limestones were intensely chemically weathered, and a large fraction of the mobilised ^{226}Ra was adsorbed by the thin layer of clay minerals, which is usually developed above limestone.
The geological profile of the Ruhr district is made up of Palaeozoic to Quaternary sediments (Fig. 1). ^{222}Rn concentrations measured within the soil gas above the different geological units clearly differs and these data are compiled in Table 3. Highest ^{222}Rn concentrations were observed in soils above Lower Carboniferous sediments and Quaternary moraine deposits. Especially black shales (alum shales) within the Lower Carboniferous strata are enriched in ^{226}Ra, with concentrations up to 500 Bq/kg (Wiegand 1997). The high ^{226}Ra concentrations of the alum shales are recognised by high ^{222}Rn concentrations of the soil gas above the shales (Fig. 3). The section in this

Table 2
^{238}U concentrations of common rocks (after Kemski and others 1996a)

Type of rock	^{238}U concentration (Bq/kg)	
	Average	Min–max
Acid magmatic rocks	44	38–250
Intermediate magmatic rocks	19	13–100
Basic magmatic rocks	11	4–13
Ultrabasic magmatic rocks	1	0.1–1
Sandstones	20	6–38
Mudstones	34	25–100
Carbonate rocks	23	4–29
Bauxite	144	25–340
Black shales	–	38–15.000
Phosphatic rocks	–	630–11.000
Continental crust	32	–
Soil	40	–

Table 3
^{222}Rn concentrations in soil gas (depth of 0.8 m) above rocks of the investigated area. Given values are medians, and number of measurements are shown in parentheses

Stratigraphy	Lithology	^{222}Rn concentration of soil gas (Bq/l) (n)
Quaternary	Loess	37 (55)
	Morainic deposits	62 (29)
	Terrace deposits (mud, sand, gravel)	39 (27)
Upper Cretaceous	Mudstone, marl	22 (36)
Upper Carboniferous	Interbedding of sand- and mudstone	27 (84)
Lower Carboniferous	Black shale, mud stone, limestone	67 (76)

figure crosses an anticline buildup by Lower Carboniferous rocks north of Wuppertal (Fig. 1). The ^{222}Rn concentrations between the alum shales and the other Lower Carboniferous sediments from the anticlinal core are well defined.
The median ^{222}Rn concentrations above the Lower Carboniferous strata are not much lower than the ^{222}Rn concentrations above the Quaternary moraine deposits (Table 3). The high concentrations can be traced back to enhanced ^{226}Ra concentrations of the deposits, which can be explained by a high content of granitic material with increased ^{238}U and ^{226}Ra concentrations (cf. Table 2).
The soils of the Quaternary terrace deposits have a medium level of ^{222}Rn concentrations (39 Bq/l, Table 3) compared with the median of all measurements (43 Bq/l, Table 1). However, the median of the terrace deposits is characterised by a bimodal distribution. In particular, fine-grained deposits with higher contents of soil moisture show high concentrations. Measurements conducted above sand and gravel deposits resulted in low concentrations because of the poor emanation conditions.
As well as the terrace deposits, the Quaternary loess cover is characterised by a medium level of ^{222}Rn concentrations (Table 3). The very stable level of all measurements is explained by the origin of these deposits. Because of the aeolian transport and sedimentation, loess is built up monotonously, and the bedding is horizontal. Thus, no strong variations in petrological or physical soil features are to be expected.
A relatively low level of ^{222}Rn concentration occurs within soils upon Upper Carboniferous and Upper Cretaceous sediments (Table 3). Whereas the measurements above the latter resulted in relatively similar concentrations, the measurements on Upper Carboniferous rocks varied strongly. On the one hand, the differences in thickness of the strata (UpperCarboniferous: 5,000 m, Upper Cretaceous: 250 m) can explain this. On the other hand, the bedding of the Cretaceous sediments is only slightly inclined, whereas the Carboniferous strata is intensely folded and, therefore, sudden lithological changes at the Earth's surface are common for the latter.
The age of the sediments should not influence the soil ^{222}Rn potential, even if Kies (1996) found a very interesting positive correlation between ^{222}Rn concentrations in dwellings and age of sediments. Usually, it is more important to identify the lithology of a bedrock and to check the rock type for potential ^{226}Ra concentrations (Table 2). Nevertheless, a correlation between ^{222}Rn concentration and the age of soils was observed within the investigated area, showing highest ^{222}Rn concentrations of soil gas on old erosion surfaces. At these sites, the bedrock is deeply weathered and a large fraction of mobilised ^{226}Ra was adsorbed on mineral surfaces, resulting in high ^{222}Rn emanation rates.

Relief

Investigations in hilly areas have shown that the distribution of ^{222}Rn concentrations in soil gas depends on the relief and the season (Tanner 1986; Janssen and others 1991, Gammage and others 1992; Arvela and others 1994; Wiegand 1994). Under natural conditions, the geological situation determines the soil development and the soil ^{222}Rn potential in first approximation. Within one geological unit (same petrography) the potential is modified

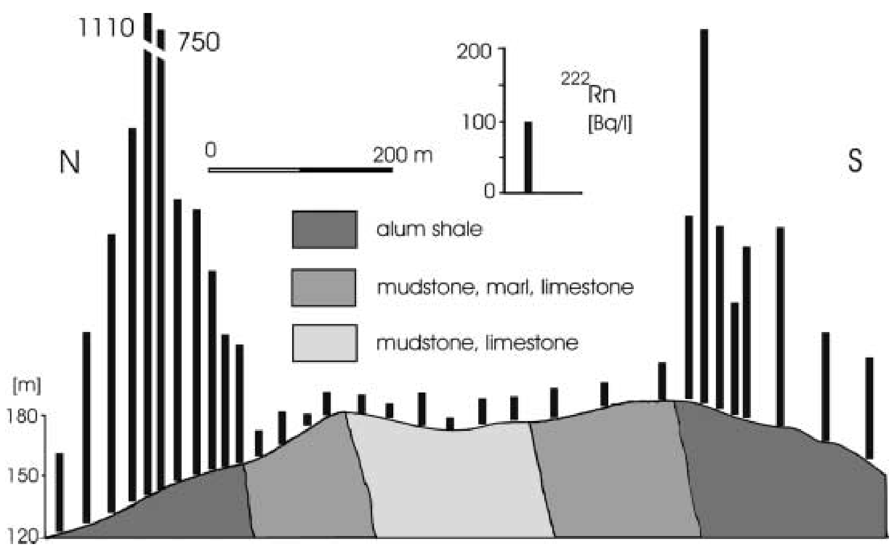


Fig. 3
Section crossing an anticline showing ^{222}Rn concentrations (depth of 0.8 m) in soil gas. The unit Hangende Alaunschiefer (alum shales) is underlain by two series of mudstones and carbonate rocks, which are grouped as Kohlenkalk

further by relief, which can be expressed as soil type variety because the soils developed with a strong dependence on the topographical situation under similar climatic conditions.

In hilly parts of the Ruhr district it was observed that the ^{222}Rn concentration of soil gas could extend over a factor of 50 during the summer, even within the same geological and lithological unit. To achieve abetter insight into the influence of the topographical and seasonal situation on the soil ^{222}Rn potential, a test site with 11 measuring points was established and investigated over a period of 3 years (Fig. 4). The bedrock of the test site, which lies at the southern rim of Essen (Fig. 1), consists of an Upper Carboniferous sandstone, which dips parallel to the slope. The ^{222}Rn concentrations shown in Fig. 4 are median values of the measurements conducted throughout the whole period (n=21–25). Parallel to the median soil moisture contents, the ^{222}Rn concentrations increased down the slope. If the measurements are grouped into summer and winter seasons, the distribution of ^{222}Rn concentrations differs strongly (factor of 20 for medians at measuring point 1). Although winter (October–March) concentrations along the slope are very similar, they show a strong gradient along the slope during the summer season (April–September): very small concentrations at the top of the slope, increasing concentrations until the lower slope part is reached, and finally a decrease again at the foot of the slope. This succession is caused by the soil development along the slope, whereby fine-grained material has been transported downslope. The distribution of fine-grained material along the slope and its good correlation with soil moisture are shown in Fig. 5. Both a high fraction of fine-grained material and a high content of soil moisture increase the emanation rate of a soil. During summer, the grain size and moisture content control the emanation rate and, therefore, the ^{222}Rn concentrations of the soil gas. If the soil moisture content gets too high (indicating that even larger soil pores are filled with water), the ^{222}Rn migration is hindered, resulting in slightly lower ^{222}Rn concentrations – a situation that often occurs at the base of a slope (Fig. 4). The same interactions between grain size, soil moisture and ^{222}Rn concentration can be observed in microrelief: Convex buckling along a slope is similar to hilltops and, vice versa, concave areas,

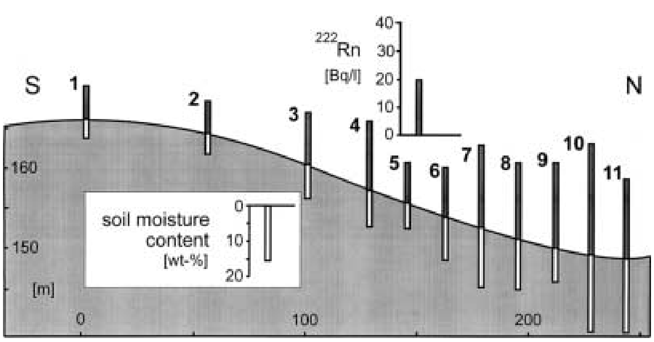


Fig. 4
^{222}Rn concentrations and soil moisture content (median values, depth of 0.8 m) along the test slope

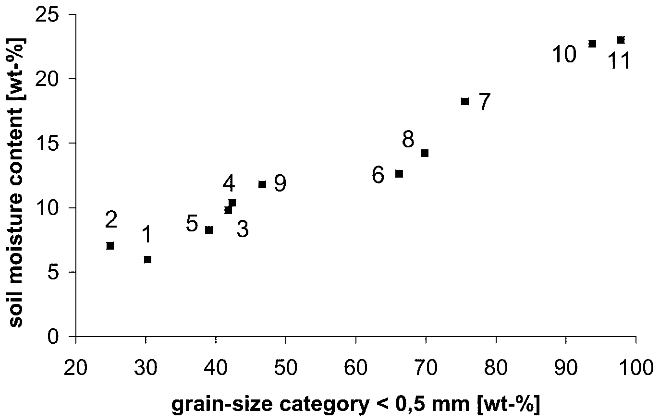


Fig. 5
Correlation of soil moisture content and fine-grained soil fraction (median values). The *numbers* indicate the measuring points of Fig. 4

such as small depressions, have a higher content of fine-grained material and soil moisture, and consequently higher ^{222}Rn concentrations.

The author compiled summer ^{222}Rn measurements along ten different slopes above Carboniferous, Cretaceous and Quaternary sediments (Wiegand 1996). To compare the measurements, the different levels of ^{222}Rn concentrations as well as the dimensions of the slopes were standardised and plotted into one diagram, which resulted in nearly the same ^{222}Rn distribution as shown in Fig. 4.

Based only on the ^{222}Rn concentrations of the soil gas, it is not possible to distinguish between a diffusive and a convective fraction of ^{222}Rn. Therefore, ^{222}Rn exhalation rates were measured to allow an identification of the migration process (Fig. 6). The diagram gives the exhalation rates over a period of 2 years for the top and the foot of the test slope. During summer, the exhalation rates were

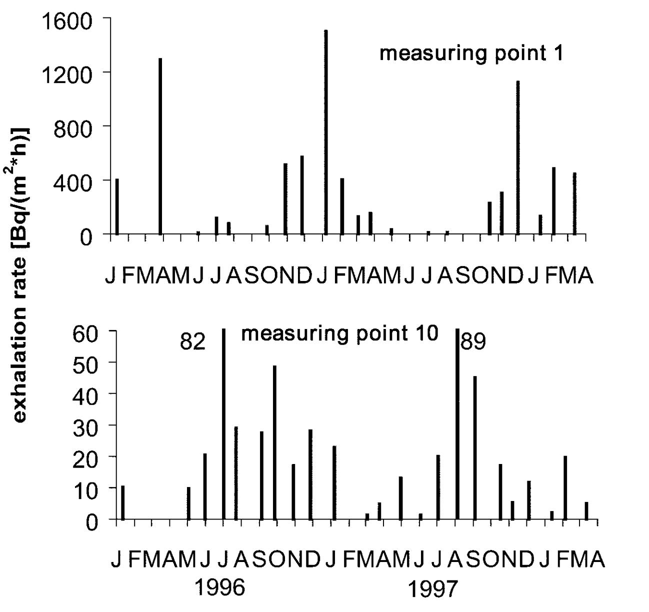


Fig. 6
^{222}Rn exhalation rates over a period of 2 years at measuring points 1 and 10 (Fig. 4)

similar to the ^{222}Rn concentrations: low rates at the top (measuring point 1), and high rates at the foot of the slope (measuring point 10). The above-described mechanisms, resulting in the distribution of ^{222}Rn concentrations during summer, are also responsible for the exhalation rates. Therefore, the ^{222}Rn migration in summer is mainly controlled by diffusive processes.

During the winter seasons (there was no snow and no frost during measurements), a significant thermal effect was observed. Driven by a strong gradient between the soil-gas temperature (warm) and the atmospheric temperature (cold), a convective flow of ^{222}Rn is established, which results in extremely high exhalation rates at the hilltops, where the soils are dry and permeable (Fig. 6, measuring point 1). The permeability of the dense and wet soils at the foot of the slope is too small to allow a convective flow of ^{222}Rn. It is even too small to allow a diffusive migration, so the exhalation rates are close to zero (Fig. 6, measuring point 10).

These observations correspond to the findings of Arvela and others (1994) for a high permeable esker in Finland. Although Arvela and others attribute the ^{222}Rn distribution only to convection (during summer: seepage of cold soil gas at the foot of the slope), the observed low permeabilities at the foot of the slope at the test site make convective processes during summer more unlikely.

The influence of relief on soil ^{222}Rn potential is complex and temporally variable. On the one hand, it is important to consider this parameter in the course of radon potential mapping, whereby the regional distribution of ^{222}Rn concentrations of the soil gas is measured (for example Kemski and others 1996b). With respect to the findings of this study, the measuring points should be placed at the lower part of the slopes. These sites are not only characterised by the highest ^{222}Rn concentrations, but they show relatively constant concentrations throughout the year. On the other hand, relief plays an important role in the entry rate of ^{222}Rn into buildings. Because the critical months for ^{222}Rn entry are the winter months (Nazaroff and Nero 1988), the elevated ^{222}Rn concentrations, and especially the high exhalation rates of the hilltops, suggest that these sites will have the highest ^{222}Rn entry rates into buildings as well. This is underlined by the findings of Janssen and others (1991) and Arvela and others (1994). They observed hilltop/foot of slope ratios of indoor ^{222}Rn that averaged 1.8 and 5 respectively during winter. In contrast, the results of our own investigation show that the same ratio for soil gas ^{222}Rn is close to a value of 1, indicating the importance of the exhalation rate for the soil ^{222}Rn potential.

Vegetation cover

There are not many investigations concerning the influence of vegetation on soil ^{222}Rn potential (Lewis and MacDonell 1986; Morris and Fraley 1994; Feige and Wiegand 1998). The parameter vegetation can be subdivided further into two different processes: a direct influence of the vegetation on the potential, and an indirect influence. The direct influence describes the ^{222}Rn transport through plants. In the course of plant transpiration, plants take up ^{222}Rn-laden soil water and release ^{222}Rn to the atmosphere. Therefore, vegetation can be thought of as a ^{222}Rn pump (Feige and Wiegand 1998).

The indirect influence deals with the impact of the vegetation onmeteorological and physical soil conditions, such as a change in the microclimate or a change in gas permeability and moisture content of soils. Solitary trees were chosen as test sites, and up to eight measuring profiles were grouped radially around them (Fig. 7). At a distance of >7 m from an oak, the ^{222}Rn concentrations of the soil gas were stable (~4.5 Bq/l). The low concentration is explained by the bedrock (Quaternary sands), which usually has a low soil ^{222}Rn potential. Near the tree, the concentration decreases significantly down to 1 or 2 Bq/l. Simultaneously conducted measurements of gas permeability and moisture content of the soils resulted in increasing permeabilities and decreasing moisture contents closer to the tree. As expected, the oak tree reduces the soil-moisture content (^{222}Rn pump), but enhances the soil permeability by root penetration. Both parameters lead to a reduction in ^{222}Rn concentration because the dry soil weakens the emanation and the high permeabilities enhance the^{222}Rn loss from soil (high exhalation).

The negative correlation between ^{222}Rn concentration and gas permeability of soils, depending on land use or vegetation cover, is illustrated in Fig. 8. Horizontally bedded sandy marls of Upper Cretaceous age are the bedrock of all 37 measurements. The lowest concentrations combined with highest permeabilities occur in forests where trees form a dense network of roots. Meadows and fields show similar values, but usually fields have lower ^{222}Rn concentrations and higher permeabilities. Although the values for meadows are relatively stable, the kind of agricultural use and the state of cultivation can strongly modify concentrations and permeabilities of fields.

The spectrum of vegetation cover in urban areas differs noticeably from the spectrum found in rural regions. For the latter, the influence of vegetation on soil ^{222}Rn potential is very important. Within cities, areas with vegetation cover are rare, and the vegetation is more uniform. Fields and forests are absent, and parks dominate, which are usually a mixture of forest and meadow, and which do

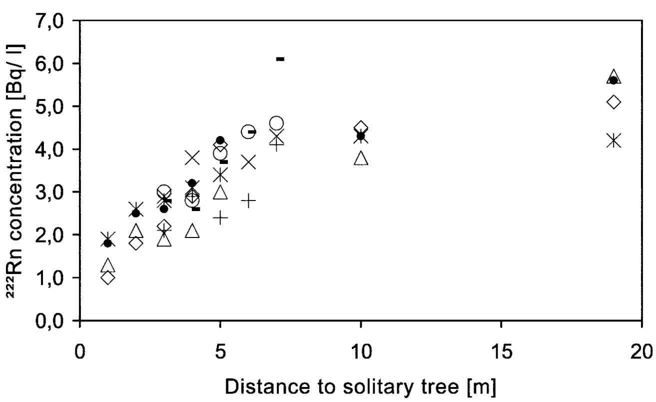


Fig. 7
^{222}Rn concentrations in soil gas (depth of 0.8 m) around an oak tree SE of Wesel (Fig. 1). The *symbols* represent radial measuring profiles

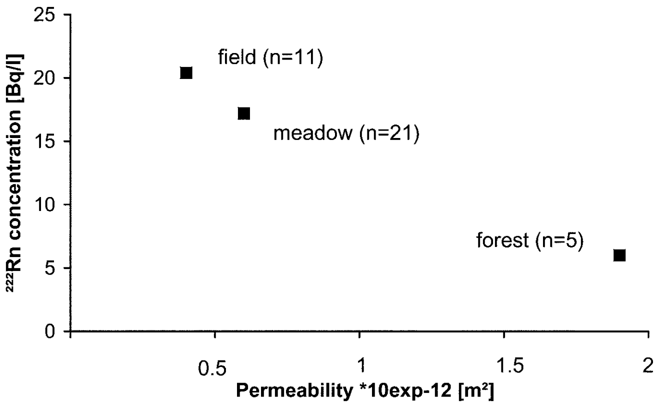


Fig. 8
Correlation between ^{222}Rn concentrations and gas permeability of soils (depth of 0.5 m) measured under different vegetation covers NW of Recklinghausen (Fig. 1)

indeed show ^{222}Rn concentrations and soil permeabilities that lie in-between.

Local parameters of soil ^{222}Rn potential

The main parameters controlling the soil ^{222}Rn potential on a more regional scale have different foci for rural and urban areas: the variety of rocks, relief and vegetation (rural areas); and the occurrence of made grounds, variety of rocks and relief (urban areas).These parameters can be modified further by geogenic and anthropogenic parameters that appear on a more local scale.

Occurrence of faults

The increase in soil ^{222}Rn potential in the vicinity of faults is often used to identify andmap them(Mogro-Campero 1977; Kemski 1993; Wiegand 1994). Nevertheless, processes leading to a positive ^{222}Rn anomaly along faults are frequently misunderstood. Fig. 9 shows an example of a measuring profile that crosses a fault perpendicularly. The bedrock is built up by an interbedding of Upper Carboniferous sand and mudstones, which are overlain by a loess cover with a thickness of 1–2 m. The measurements were done within the loess (depth of 0.8 m), and the fault was traced through the thin Quaternary cover. Very often, such an anomaly is attributed to an increase in gas permeability along the fault and, therefore, to an increase in convective ^{222}Rn (for exampleKemski 1993). This can be true if the measurements were conducted during the winter season, when there is a strong temperature gradient pointing from the soil to the atmosphere. However, the measurements shown in Fig. 9 were made during the summer, when an increase in permeability should result in lower ^{222}Rn concentrations.

To understand ^{222}Rn anomalies along faults, other physical soil parameters must be taken into account. First, faults are notalways zones of high soil permeability (clay stemming), which makes it more complicated to interpret anomalies (Neznal and others 1991). Second, cataclastic processes lead to an enlargement of the rock surface and to a higher soil moisture content, which are both parameters that increase the ^{222}Rn emanation and, therefore, the concentration. Third, Lauterbach (1968) and, more recently, Toth and others (1997), Choubey and others (2000) recognised that alteration processes occur frequently along faults, which can enrich ^{238}U and ^{226}Ra, resulting in a geochemically based ^{222}Rn anomaly.

Man-made faults, such as those that develop in the course of underground mining and subsequent mining subsidence, behave differently with respect to soil ^{222}Rn potential. Some of these faults are reactivated natural ones, but most of them are new. All these artificial faults are characterised by a lack of mylonitisation, and very limited cataclasis, and all of them have increased gas permeabilities (no clay stemming). Furthermore, they are much too young to develop a ^{226}Ra anomaly. Such a man-made fault was identified by a linear subsidence crossing a street, which resulted in a 40-mm-wide crack in the asphalt (Fig. 10). Perpendicular to the fault, measurements of ^{222}Rn concentrations in soil gas were conducted several times over a period of 1 year. Besides positive ^{222}Rn anomalies, negative ones occurred as well. Here, a differentiation of diffusive and convective fractions of the ^{222}Rn concentration was possible: while the convective conditions were marked by positive anomalies, the prevalent diffusive conditions resulted in negative anomalies.

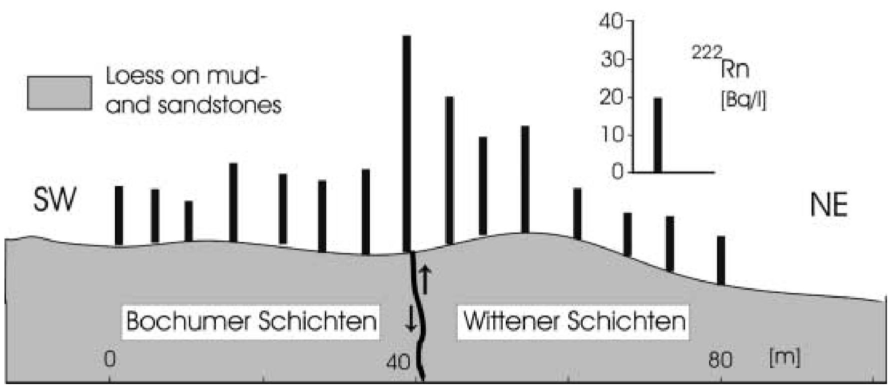


Fig. 9
^{222}Rn concentrations in soil gas (depth of 0.8 m) in the vicinity of a fault south of Essen (Fig. 1). The Wittener and the overlying Bochumer Schichten belong to the Upper Carboniferous Westfal A

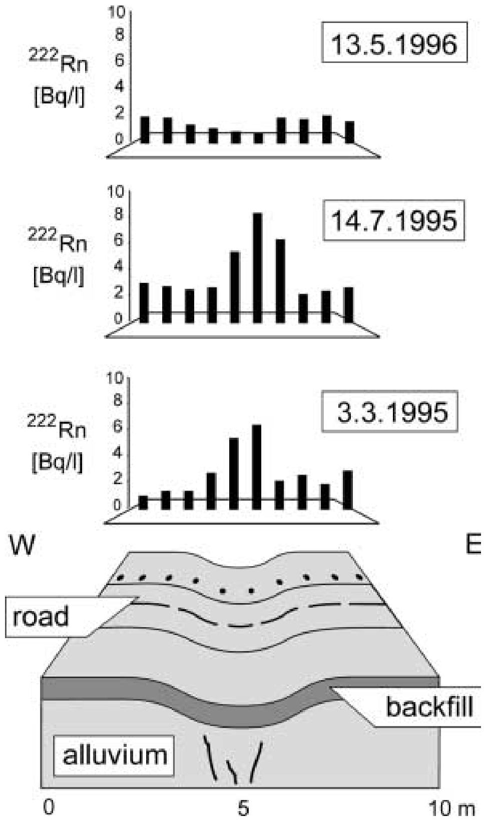


Fig. 10
^{222}Rn concentrations in soil gas (depth of 0.8 m) in the vicinity of a man-made fault north of Recklinghausen (Fig. 1)

The occurrence of faults can be of great importance for indoor ^{222}Rn. In particular, permeable faults enable a large fraction of convective ^{222}Rn to occur during the winter season, just like on hilltops. For buildings in the vicinity of man-made faults a second mechanism becomes important: even slight damage to the foundation, such as small cracks, can be used as ^{222}Rn entry pathways, resulting in a doubling of indoor ^{222}Rn (higher soil ^{222}Rn potential and better ^{222}Rn entry).

Sealing of soils

It is known that natural soil sealing by frost and snow cover has an impact on the soil ^{222}Rn potential (Fleischer and Likes 1979; Tanner 1980; Taipale and Winquist 1985). Thereafter, sealing of soils result in a reduction of exhalation, but an increase in^{222}Rn concentrations beneath the sealing. Investigations on the influence of artificial soil sealing through roads, squares and buildings are very scarce (Wiegand and Schott 1999). Such artificial sealing can be important anywhere, but it is especially important in urban areas, where the degree of sealing varies between 50 and 100% (Table 4).

To identify the influence of soil sealing on soil ^{222}Rn potential, measurements of ^{222}Rn concentrations in soil-gas and exhalation rates were conducted throughout the Ruhr district. Figure 11 shows one of the test sites – an area between two bifurcating roads NW of Essen (Fig. 1). Comparable to the process of infiltrating precipitation,

Table 4
Degree of soil sealing in dependence of land use (after: Blume 1996)

Degree of sealing (%)		Land use
0–15	Low	Agrarian country, forest, park, allotment, cemetery, airport and sports field (the last two are partly only moderate)
15–50	Moderate	Detached buildings and terraced houses with garden
45–75	Medium	Buildings in a row with community greens, public buildings
70–90	Strong	Blocks with high site density, trade and industry
85–100	Very strong	City centres, partly industrial

upward migrating ^{222}Rn is concentrated at the rims of the sealing, resulting in a good correlation between ^{222}Rn concentrations in soil gas and the degree of sealing. Similar results were obtained at other test sites, where ^{222}Rn measurements were made at different depths, and exhalation rates were also determined (Wiegand and Schott 1999).

For a better insight into this parameter, and to be sure that the material beneath the sealing is homogeneous, a test site was established upon monotonous Cretaceous sands north of Recklinghausen (Fig. 1), where the soil cover was removed. A 35-m^2, ^{222}Rn-tight, high-density polyethylene foil was chosen as sealing, and ^{222}Rn concentrations at different depths as well as exhalation rates were measured several times during the summer and winter seasons (with and without foil). It was observed that the influence of meteorological conditions on soil ^{222}Rnpotential was enforced under a high degree of sealing. Precipitation increased the soil moisture content close to saturation, resulting in a sharp decrease in exhalation rates and a later washout of ^{222}Rn from soil gas. On the other hand, a drop in air pressure stimulated ^{222}Rn migration most strongly under the highest degrees of sealing.

Compilation of all measurements of the test site showed that the effect of sealing on ^{222}Rn concentrations increased from deeper to shallower soil levels. This is confirmed by modelling the increase in concentrations under the ge-

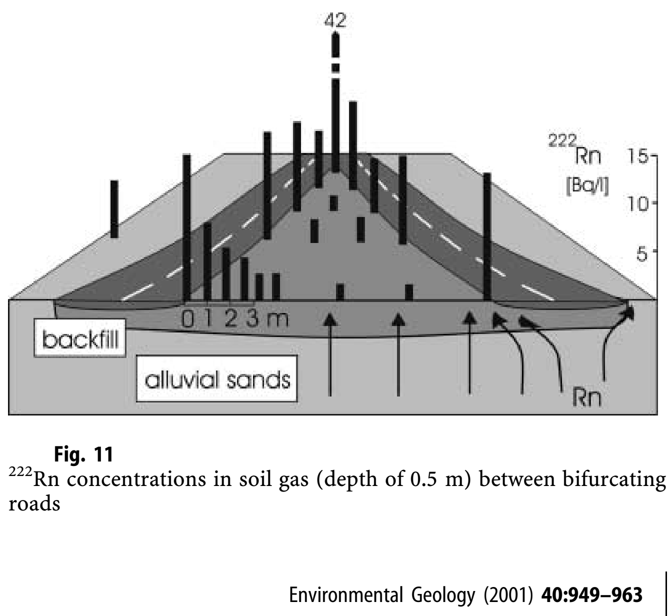


Fig. 11
^{222}Rn concentrations in soil gas (depth of 0.5 m) between bifurcating roads

ometry of measurements and the physical soil conditions of the test site (Fig. 12). The modelling, which was conducted by Wim van der Spoel (Spoel and others 1999), is based on a circular sealing (r=5 m), with a hole (r=0.15 m) at its centre. The diagram shows only the modelling of the inner part of the radius (r=1 m). The results of the actual, measured increase in ^{222}Rn concentrations (boxed numbers,Wiegand and Schott 1999), depending on soil depth (0.3, 0.5, 0.8 m), are in relative good agreement with the modelled increase.

With the same physical soil conditions and parameters, the modelling was done for a sealing situation that was more comparable to roadsides or foundations of buildings (Fig. 13). The results are shown now for a radius and depth of 5 m. Under the conditions of the chosen bedrock (unconsolidated medium-grained sand), the increase in ^{222}Rn concentrations is traceable up to adistance of 1 m to the sealing, and up to a depth of 2–3 m beneath the sealing. The situation modelled in Fig. 13 matches the case of buildings without a cellar. If the buildings are surrounded by a sealing, the loss of ^{222}Rn to the atmosphere close to the edges of the foundation will be smaller and, therefore, the ^{222}Rn concentrations in soil gas and the entry rate into buildings will be higher. In the case of buildings with a cellar, the foundations may reach a depth of 2.5 – 3 m, where the increase in ^{222}Rn concentrations is close to zero. However, now the walls of the cellars are important as potential entry pathways for ^{222}Rn, and the concentrations of soil gas near the walls will be higher in the case of sealing the soil. Such interactions between the sealing of the soil and the ^{222}Rn entry rate into buildings are very important in city centres of urban areas, where the degree of sealing is close to 100% (Table 4). Nevertheless, the interaction between individual buildings, such as terrace houses, will enhance the ^{222}Rn entry into buildings in rural areas as well.

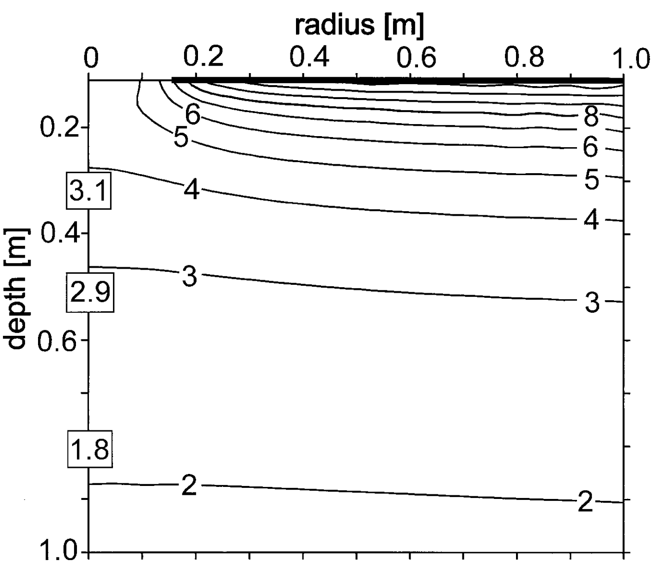


Fig. 12
Modelling the increase in ^{222}Rn concentrations in soil gas beneath a sealing (*thick black line*). The *boxed numbers* indicate the results of measurements

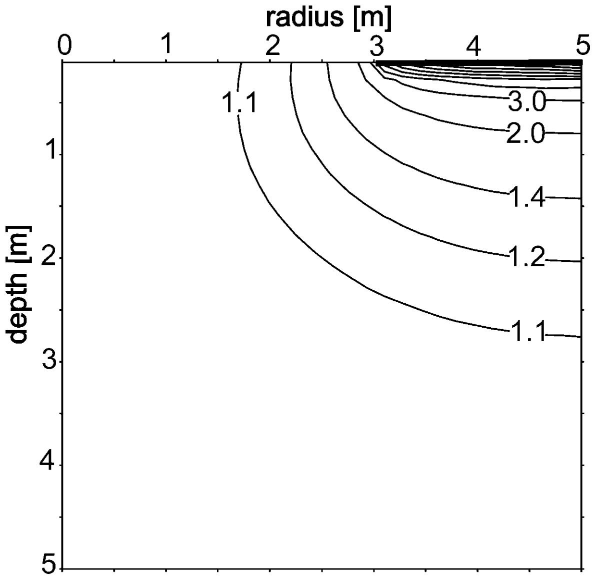


Fig. 13
Modelling the increase in ^{222}Rn concentrations in soil gas beneath a sealing

Traffic vibrations

A common feature of urban areas is anthropogenic inducedvibrations of the soil generated mainly by trains, road traffic, subways and activities on construction sites. Except for a very few studies (Schmid and Wiegand 1998), the effect of vibrations on the migration of ^{222}Rn and other soil gases has been little investigated.

Vibrations induced by trains and road traffic are surface waves with low frequencies in the range of 10–80 Hz. The analysis of the recorded signals is complicated because of frequent heterogeneous soil conditions of urban areas. Throughout the Ruhr district, trains, road traffic and construction sites were used as vibration sources, and ^{222}Rn concentrations in soil gas as well as vibrations were measured (Schmid and Wiegand 1998). At special test sites, vibrations were generated with a pneumatic drill. The strongest vibrations and the most striking impact on the ^{222}Rn concentrations in soil gas were observed in the vicinity of construction sites. In particular, when metal panels were rammed into the ground, a doubling of ^{222}Rn concentrations close to the vibration source (10 m) were measured. Even at a distance of 60 m, the concentrations were increased by about 30%.

Much weaker vibrations were generated by road traffic, which resulted in a smaller effect on soil ^{222}Rn potential. A measuring profile perpendicular to a heavily travelled road NW of Essen shows the influence of road traffic on the ^{222}Rn concentrations of soil gas (Fig. 14). The measuring point to the west, 25 m off the road, acts as a reference siteto confirm that there are no diurnal fluctuations during the measurement period. With the beginning of the rush-hour, the ^{222}Rn concentrations of the other measuring points clearly rose. The decrease in the level of ^{222}Rn concentrations within the first 2 m is not attributed to the vibrations, but to the effect of soil sealing. Compiling all measurements taken close to roads, the effect of road

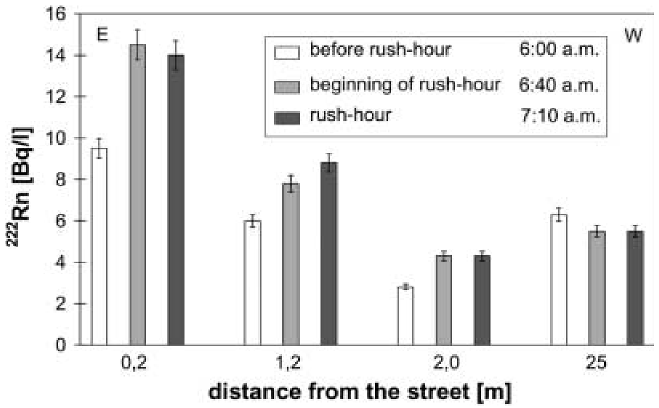


Fig. 14
^{222}Rn concentrations in soil gas (depth of 0.5 m, 1 σ counting error) close to a road (after Schmid and Wiegand 1998)

traffic on soil ^{222}Rn potential is limited to the first few metres beside the road (up to 10–15 m).

Trains as vibration sources have the advantage that we can analyse the influence of a timed, singular vibration – not like the background noise of road traffic. Figure 15 shows ^{222}Rn concentrations in soil gas determined at a measuring point 5 m away from a railroad track east of Essen (Fig. 1). The bedrock consists of an interbedding of Upper Carboniferous sand and mudstone, with a high gas permeability of the soil. Because it is not possible to measure the ^{222}Rn concentrations continuously with a high temporal resolution, each minute a grab sample was taken over a period of nearly 1 h. It became clear that each time a train passed, the ^{222}Rn concentrations increased and then declined after the train had passed. In the case of two trains passing one after another (in ~42 min), the ^{222}Rn anomaly was wider than usual. To verify the interactions between the vibrations and the ^{222}Rn concentrations in soil gas, the increase in ^{222}Rn concentrations and the magnitude of the vibration signal were calculated, which resulted in a relatively good correlation (Schmid and Wiegand 1998). Other test sites have shown that the vibrations generated by trains can enhance the ^{222}Rn concentrations by up to 400%

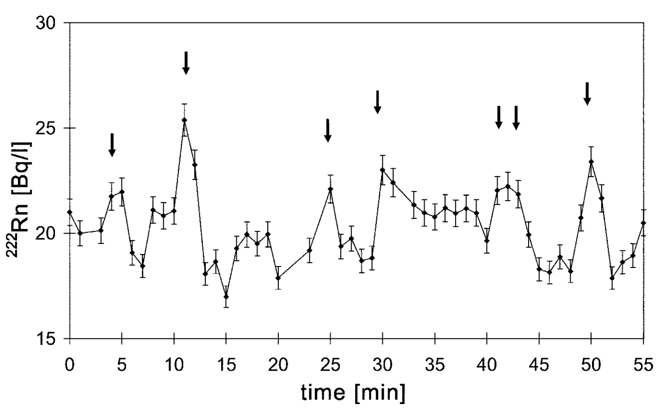


Fig. 15
^{222}Rn concentrations in soil gas (depth of 0.8 m, 1 σ counting error) 5 m off a railroad track. *Arrows* mark passage of trains (after Schmid and Wiegand 1998)

(1 m off the railway track), and up to a distance of 30–50 m (Schmid and Wiegand 1998).

The vibration-induced increase in ^{222}Rn concentrations in soil gas can be explained by a pump effect (Fig. 16). Because of subsurface vibrations, mineral grains start to vibrate, whereby soil gas is slightly blown out of the ground. This results in an upward-directed convective flow of soil gas. Therefore, during the vibrations, soil gas is sampled that comes from greater depths. Because the gradient of ^{222}Rn concentrations is very strong within the measured depths, soil gas does not need to migrate more than a few centimetres to explain the observed differences. At the test site of Fig. 15, a 5–10 cm rise in soil gas was sufficient. Although the soil in the vicinity of railway tracks is stimulated every few minutes, vibrations generated by pneumatic drills were used to investigate the vibration effect on usually "untroubled soil" (Fig. 17).The bedrock, composed of Lower Carboniferous alum shales, resulted in a strong ^{222}Rn signal but a low gas permeability of the soil. ^{222}Rn concentrations were measured over a period of 4 h and, with a pneumatic drill, a probe was drilled three times into the soil (in period of 1 min), just 2 m off the measuring point. For a better identification of the vibration effects, sampling was more frequent after the drilling started. Comparing this diagram with Fig. 15, two differences can be noted. Firstly, the vibration-induced increase in ^{222}Rn concentrations was delayed: at 5–15 min after the end of the vibrations, the concentrations began to rise. This can be explained by the different soil permeabilities of the two test sites: high permeabilities resulted in a quick response (Fig. 15), and lower permeabilities in a delay (Fig. 17). The second difference was a steady increase in concentrations during the periods with no vibrations (Fig. 17). Because this effect was only observed at test sites, which are usually not subjected to vibrations, a slight mixture of soil gas from different depths is a probable explanation. This mixture can only be partial, otherwise there would be no increase in ^{222}Rn concentrations along railroad tracks.

Through the pump effect, an upward-directed convective flow of soil gas can be triggered, which can pump ^{222}Rn into buildings. Following this model, the ^{222}Rn entry rate is higher close to traffic routes, and trains with their stronger vibration signal have a larger impact than road traffic. At a

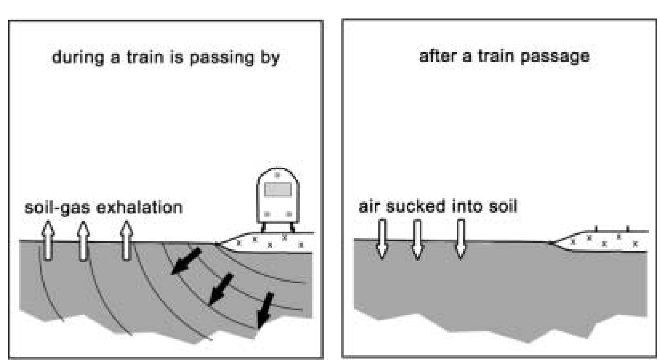


Fig. 16
The pump effect caused by traffic vibrations

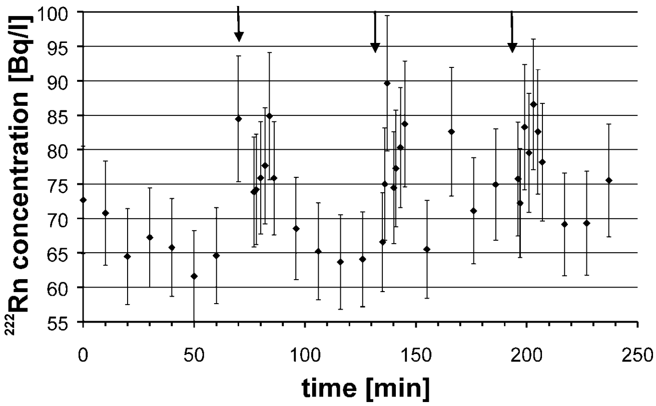


Fig. 17
^{222}Rn concentrations in soil gas (depth of 0.8 m, overall statistical error) above Lower Carboniferous sediments north of Wuppertal (Fig. 1). *Arrows* mark periods of drilling

distance of 10 m to the vibrations sources of roads, railway tracks and construction sites, an increase in ^{222}Rn concentrations of 1.05 (n=18), 1.15 (n=26) and 2.0 (n=4) were measured (0.8 m depth), which results in a mean increase in F=1.2. Vibrations caused by construction activities are strong, but rarely occur at a chosen site for this to be of great importance. Even though the parameter vibration will be the least important of the presented parameters, a coupling of different parameters, such as permeable soil and a high degree of soil sealing, together with traffic vibrations, could result in very high entryrates.

Evaluation of the soil ^{222}Rn potential

Besides a better insight into soil gas migration in general, the findings of this study can be applied in two different ways. First and more importantly, parameters of soil ^{222}Rn potential can be ranked and evaluated, and secondly, recommendations for measurements at building plots can be given to verify the local soil ^{222}Rn potential more precisely. Such recommendations are obvious from the findings presented here, and are listed only in catchwords: depth of measurements at the depth of the foundation (at least in the case when on made ground or Quaternary cover); placement of measuring points preferably downhill; consideration of the impact of vegetation, soil sealing and vibration.

A ranking and evaluation of soil ^{222}Rn potential parameters are delicate tasks, and here a ten-point system that can be used as a rule of thumb has been introduced (Table 5). This system considers soil ^{222}Rn potential only, it does not include the influences of building characteristics, like Gundersen and Schumann (1996) did. The author recommends a separation of the two main parameters for indoor ^{222}Rn (soil and architecture), and an individual evaluation of these two parameters. Because the soil ^{222}Rn potential is usually the major parameter of indoor ^{222}Rn, the author encourages colleagues with access to indoor ^{222}Rn databases to validate the correlation between the evaluated soil ^{222}Rn potential (Table 5) and the actual indoor ^{222}Rn level.

The main advantage of the ten-point system lies in the possibility to estimate the soil ^{222}Rn potential of any site – even without making measurements. The proposed system is different from the usual approach, where ^{222}Rn potential maps are produced at scales that may be too small to be satisfactory (Ball and others 1992; Schumann 1993; Barnet 1994; Shirav and Vulkan 1997). The main problems of these maps are a lack of flexibility and the impossibility to consider sudden spatial changes within the local soil ^{222}Rn potential, such as changes in lithology, relief or vegetation. Apart from some good results (for example Schumann 1993; Kemski and others 1996b), Friis and others (1999) showed a failure in geologically based ^{222}Rn risk maps. Therefore, Apte and others (1999) started to include parameters other than geology into the prediction of indoor ^{222}Rn concentrations.

This idea is followed in this study. The basis of the system presented here is a grouping of fundamental parameters of soil ^{222}Rn potential, such as concentration and distribution of ^{226}Ra in soils, or grain size, moisture content and permeability of soils. Because it is not suitable to measure the fundamental parameters at each site, these were assigned to the parameters presented here, which are already mapped (geology and occurrence of made grounds or faults), or that are noticeable (relief, vegetation, soil sealing and traffic vibrations). Furthermore, if the geogenic ^{222}Rn potential of an area is already mapped, this information is considered within the proposed system.

To apply the system, the five items of Table 5 should be answered one after another, and the corresponding points (P-values) are summed. Under the first question 'origin of soil', sites on undisturbed soils or on thin, made ground covers receivea bonus of two points, because the processes of weathering and soil development can accumulate radionuclides in soil horizons, and increase ^{222}Rn emanation. Under the item'geology', the type of bedrock or made ground is evaluated. A grouping of different rock types with respect to the resulting soil ^{222}Rn potential of their soils is difficult and never exact. The classification of main rock types from sedimentary, magmatic and metamorphic origin reflects the findings of our own and cited studies, especially from Wedepohl (1978). The grouping is based mainly on average ^{226}Ra concentrations and permeabilities, as well as known tendencies to accumulate ^{226}Ra in the soil horizon (for example limestone). It is not possible to give an average increase in ^{222}Rn concentrations in soil gas for the different groups (F-values in Table 5), because the database is not complete , and for data from the literature, a possible disturbance by other parameters (e.g. relief or vegetation) cannot be excluded. In the case of Quaternary covers >2 m, the material of the cover is of relevance (for example solifluction body from loess, or talus deposits from orthogneiss). If a geologically based ^{222}Rn potential of a considered areahas been already investigated (often in low, medium and high risk areas), this classification should be preferred instead of the proposed subdivision presented here (2.1 in Table 5). In doing so, the determined potential is divided into three groups, and 0, 1 and 3 points are assigned to these. When the geogenic potential was mapped gradually, four groups with 0, 1, 2, 3 points are suitable. The inclusion of existing geologically based ^{222}Rn potential maps is a distinct improvement to the ten-point-system. However, if there is evidence that the geological situation of a local site is under-represented with respect to the geogenic ^{222}Rn potential (like small silicic intrusive bodies in a larger quartzite sequence), the classification of the potential map should be disregarded and the subdivision proposed here should be used (worst-case-situation).

Under the third parameter 'relief', the seasonal variation of the soil potential led to the decision to disregard the summer data, because the winter is more relevant for indoor ^{222}Rn. To quantify the parameter 'vegetation', three test areas were chosen (on Palaeozoic, Mesozoic and Cenozoic sediments), and ^{222}Rn was measured at a depth of 0.5 m. The increase in ^{222}Rn concentrations from forest to field and meadow reached a mean factor of F=3, and was very stable at all test areas: 3.0 (n=37), 3.1 (n=26), 3.2 (n=36).

The local parameters are combined under item five, and when one of the three parameters is appropriate, one point is given. An estimation of a mean increase in soil gas ^{222}Rn concentrations along faults from our own results and from the literature cited here lies in the range of 1.5–3.0, with an average value of F=2.0. The mean increase in ^{222}Rn concentrations with 50% soil sealing is 1.6 (n=132, 0.5 m depth), which is in good agreement with the modelling in Fig. 13. Probably, the importance of traffic vibration is overestimated, but this evaluation is a rule of thumb, and the placing of 0.5 points should not simulate a pseudo accuracy.

Summing up all given points, the resulting score ranges from 0–10 points, whereby 0–4 points represent a low soil ^{222}Rn potential. At these sites, high ^{222}Rn concentrations of soil gas, especially in combination with high permeabilities, should be exceptions (for example: uranium enrichment in sandstones is not identified). A soil ^{222}Rn potential of 5–10 is ranked as a high potential, but only very few sites have a higher potential than 7. From >8 points, the soil ^{222}Rn potential is assumed to be very high. Inclusion of already existing potential maps into this system will always result in a score of 5–10 points for high risk areas.

Table 5
Ranking and evaluation of main parameters on the soil ^{222}Rn potential. *F* Factor of mean increase in soil gas ^{222}Rn concentrations; *P* score of soil ^{222}Rn potential. 0–4 Points: low potential; 5–10 points: high potential (≥8 very seldom)

Parameter			F	P
1. Origin of soil		Undisturbed soil or backfill <2 m (go to 2.1)	5	2
		Backfill >2 m (go to 2.2)	1	0
2. Geology	2.1 variety of rocks	Sediment: black shale, phosphate, bauxite	–	3
		Magmaticrock: rather silicic (granite, granodiorite, syenite, monzonite, rhyolite, dacite, pumice, pegmatite), and alkaline rocks		
		Metamorphic rock: orthogneiss, greisen		
		Sediment: gravel, pelite, carbonate rock, loess, till	–	1
		Magmatic rock: rather intermediate (diorite, andesite)		
		Metamorphic rock: clay schist, mica schist, paragneiss, granulite, marble		
		Sediment: sand, sandstone, conglomerate, clay, evaporite	–	0
		Magmatic rock: mafic, ultramafic (gabbro, basalt, diabase, peridotite		
		Metamorphic rock: quartzite, amphibolite, eclogite, serpentinite		
	2.2 type of backfill	High ^{226}Ra concentration: slags, ashes, sewage sludge, tailings (ore mining)	10	3
		Low ^{226}Ra concentration: sand, gravel, soil aggradation, rubble, tailings (coal mining)	1	0
3. Relief		Upper part of hill	1	1
		Lower part of hill	1	0
		Plain	1	0
4. Vegetation		Field, meadow or no vegetation	3	1
		Forest	1	0
5. Local parameters		Tectonic elements: fault, mining subsidence	2	1
		Soil sealing >50%	1.6	1
		Strong traffic vibration (trains or trucks) <10 m distance	1.2	1

However, now low and medium risk areas can reach 5 points as well, if other parameters superimpose the geologically based potential.
On-site measurements for an evaluation of the actual ^{222}Rn risk, whether in soil or indoors, are not recommended below a soil ^{222}Rn potential of 4. Measurements are not necessary if there is a potential of 5 or higher, and the ^{222}Rn risk of a construction site should be determined. In this case, it is recommended to construct ^{222}Rn-safe buildings directly. In the case of existing buildings, ^{222}Rn measurements are necessary. Such measurements should be done preferably in winter, and then directly in the building, where the actual ^{222}Rn exposure can be determined.

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