Radon over Kimberlite Pipes: Surface Field Experiments and Calculations of Vertical Diffusion (Arkhangelsk Diamondiferous Province, NW Russia)

Evgeny Yakovlev * and Andrey Puchkov

N. Laverov Federal Centre for Integrated Arctic Research of Ural Branch of the Russian Academy of Sciences, 109 Severnoj Dviny Emb., 163000 Arkhangelsk, Russia; vp-andrew@list.ru
* Correspondence: evgeny.yakovlev@fciarctic.ru; Tel.: +7-931-401-41-08; Fax: +7-8182-28-76-36

Abstract: We present the results of field and experimental studies to assess the influence on the formation of the radon field over the kimberlite pipes of the Arkhangelsk diamondiferous province. Measurements were made in the field to establish the radon radiation in the soil air and the gas permeability of soils in the area of the Chidvinskaya pipe. Experimental work was aimed at determining the radiation and physical parameters of the rocks occurring within the kimberlite field. Based on a set of field and experimental data, a model of the diffusion transfer of radon in the area of the Chidvinskaya pipe was calculated for three profiles, represented by the rocks of the pipe, sedimentary rocks of the exocontacts of the pipe, and host sandy and clay sedimentary rocks. The results of the calculations show that the rocks of the exocontacts of the pipe have the greatest potential for increased radon radiation. The calculated values of the radon radiation produced by these rocks exceeded 9000 Bq m\(^{-3}\). The diatreme kimberlites produced the lowest radon radiation. We showed that the source of the increased values of radon radiation is the rocks of the pipe’s exocontacts. This fact will make it possible to use the emanation method as an additional one for the search for kimberlite pipes.

Keywords: radon; diffusion; permeability; kimberlite pipe; Arkhangelsk diamondiferous province

1. Introduction

The radon-222 isotope is constantly formed in almost all natural environments during the radioactive decay of its parent radium-226 isotope. The half-life of radon is 3.82 days [1–5]. Radon is an inert gas, the physical and chemical properties of which allow it to be used as an optimal indicator for studying the processes occurring in the environment [4,6–10]. First of all, radon is used as a tracer in its “free” state, which allows it to migrate freely in various media both in gaseous form and as a water-soluble compound [3,11–13]. This process leads to the appearance of an emanation field in the near-surface horizons of rocks, grounds, and soils [3,14,15]. The analysis of emanation fields is widely used in geochemical, geophysical, and geodynamic research [4], including the search for mineral deposits [16–19].

Emanation studies carried out on the territory of the kimberlite fields of the Arkhangelsk diamondiferous province showed that anomalous values of radon radiation are observed above the kimberlite pipes [20,21]. The authors showed that the nature of the distribution of radon over kimberlite pipes has a sub-annular shape, which is associated with the development of faults and fractures of the host lithologies [19,22]. To explain the formation mechanisms of such radon fields, we carried out experimental work [23] to identify the radiation and physical parameters of the rocks of the kimberlite pipe. We showed that diatreme kimberlites are characterised by low values of emanation coefficient, the level of porosity, the activity of radium-226, and radon production rate. In turn, the country rocks, represented by the host Ediacaran sedimentary rocks V\(_2\), produce the highest amounts of radon in “free” state and are characterised by high values of radiation and physical parameters (porosity, permeability).
The radon radiation largely depends on the geological, geochemical, physical and radiation characteristics of the object [4,24,25]. Some authors [3,4,26–30] have paid attention to the porosity, density, and permeability of the rocks, which in turn depend on the temperature processes (as well as tectonic) that occur after magmatic crystallisation. Radon can enter the surrounding space both due to radioactive recoil and due to diffusion. To understand these processes, scientists have developed mathematical models of radon transport in solid geological media. There are three groups of radon transport models: diffusion (based on the diffusion equation) [31–36], convection [37,38], diffusion–convection and diffusion–advection [39]. However, the latest calculation results obtained from convection and diffusion–convection models show a low level of comparability with experimental data. This is due to the fact that the calculated versions of the models, as a rule, are very simplified, and most of them require very specific input parameters, which in some cases cannot even be determined for a real system [40]. The group of diffusion models show good results in convergence with experimental data, and at the moment, the diffusion mechanism is considered to be the main one for radon transfer process [36]. The results of modelling the processes of radon transfer are of great importance in radioecology, geological exploration and geophysics, for example, in the study of lithospheric–atmospheric relations, or the search for earthquake precursors or fossil deposits [41].

The main purpose of this work is to study the distribution of radon radiation and the gas permeability of soils in the territory of a kimberlite pipe, as well as to calculate a model of diffusive radon transport along three profiles (pipe, near-pipe space, sandstones with siltstone interlayers of Ediacaran sedimentary rocks) using the results of the work [23]. In this work, we calculated the radiation and physical characteristics of the host rocks and kimberlite.

2. Material and Methods

Field studies were carried out in the territory of the Chidvinskaya pipe, which is part of the Chidvinsko-Izhmozersky field of the Arkhangelsk diamondiferous province (NW Russia, Figure 1). The Chidvinsko-Izhmozersky field is located 30 km northeast of the city of Arkhangelsk and includes six kimberlite pipes, forming a 20 km-long chain stretching along the ore-controlling fault with a north-northeast direction [42,43]. The Chidvinskaya pipe is the largest and most studied pipe in the Chidvinsko-Izhmozersky field. The dimensions of the pipe are 1810 × 580 m. In projection, the pipe has an irregular dumbbell shape. The rocks hosting the Chidvinskaya pipe are sandstones with siltstone interlayers of Ediacaran sedimentary rocks, represented by a mixture of siltstones, mudstones, and sandstones. The overlying layer is represented by Quaternary deposits, which consist mainly of sands, peat and pebbles. The average thickness of the overlying Quaternary deposits is 9.4 m. In the northern part of the pipe, the thickness of the overlying sediments decreases to 1.5 m. Among the known pipes of the Arkhangelsk diamondiferous province, the Chidvinskaya pipe has the smallest thickness of overlying sediments [44], which is important for radiometric field studies.

The body of the pipe consists of pyroclastic kimberlite, tuffs, and volcanioclastic kimberlite, the formation time of which has been dated to the Upper Devonian-Middle Carboniferous D3-C2. The contacts between diatreme and the hosting sediments are clearly visible. The thickness of the contact zone exceeds 10 m. The Chidvinskaya pipe has a low diamond content and is currently of no commercial importance. However, this could be attributed to the small amounts of sampling which might give a low level of reliability in the estimates of the diamond content of the pipe [44]. Currently, additional exploration of the pipe is planned to clarify its diamond reserves [45].

Radiometric field studies in the area of the Chidvinskaya pipe were carried out along a network of profiles crossing the pipe in the NW-SE direction. The distance between the measurement points varied depending on the specific landscape situation, but did not exceed 100 m. A total of 118 points were selected. At each point of measurement in the field, radon radiation and soil gas permeability were determined. Specialists of the
Laboratory of Environmental Radiology of the Laverov Federal Center for Integrated Arctic Research (Arkhangelsk city, Russia) applied the emanation method to determine the radon radiation, using the radon radiometer “Alpharad plus” (Manufacturer-“NTM” Protection, Moscow city, Russia). Gas permeability was determined using the RADON-JOK system (Manufacturer-RADON v.o.s. corporation, Prague, Czech Republic).

Figure 1. Location map of the Chidvinskaya pipe and the location of the profiles for calculating the vertical transport of radon.

The calculation of radon transport along three profiles (kimberlite pipe, country rocks, sandstones with siltstone interlayers of Ediacaran sedimentary rocks) was made on the basis of the radon diffusion model under homogeneous and single-layer conditions. The layout of the profiles is shown in Figure 2. For this, we used the previously measured radiation and physical parameters of the host rocks and kimberlite [23].
2.1. Radiometric (Emanation) Measurement Method

The measurement of radon radiation using “Alpharad Plus” is based on the electrostatic deposition of charged Po-218 (RaA) ions from the air sample to the surface of the semiconductor detector. The electrical impulses generated under the influence of alpha particles on the detector were amplified with a preamplifier, fed to the input of an analogue-to-digital converter, and then processed with a computer. The measurement results were displayed on a colour LCD screen and stored in non-volatile memory. The radon radiation was determined by the number of registered alpha particles during the decay of RaA atoms deposited on the detector [46].

To install the samplers, boreholes were drilled at key points with a diameter of 3 to 5 cm and a depth of 0.7 to 1 m. The number of key points was determined by the need to study variations in radon radiation within the kimberlite body, at contacts with the host environment, and also considering the background radiation outside the pipe. The installation of the samplers was carried out in a suspended state with the subsequent sealing of the borehole neck with soil. The exposure time of the sampler in the borehole, required to equalise the radon radiation in the soil air and in the sampler, ranged from 12 to 18 h. After the end of the exposure, the sampler was removed and sealed with plugs. Measurements using a radon radiometer were carried out no more than one hour after removing the sampler from the borehole.
2.2. Field Method for Measuring the Gas Permeability of Soils

The determination of the gas permeability parameter was carried out at each point of measurement of the radon radiation. We used RADON–JOK device (Manufacturer-RADON v.o.s. corporation, Prague, Czech Republic) to measure soil permeability.

The principle of operation of the RADON-JOK system is to vent air at a set negative pressure. Air is pumped out of the soil through a specially designed steel hollow probe. A permanent working area is created in the probe head by extruding the tip with a steel rod (core) inside the probe at a certain distance. Air is pumped out of the soil into a sealed rubber bag. Gas permeability is then calculated based on the equation for determining the air flow through the cavity of the probe:

\[ Q = F \cdot \left( \frac{k}{\mu} \right) \cdot \Delta p \]  

where:
- \( Q \) — air flow through the hollow probe, m\(^3\)·s\(^{-1}\);
- \( F \) — form factor of the probe (depends on the geometry of the measurement), m;
- \( k \) — soil gas permeability parameter, m\(^2\);
- \( \mu \) — dynamic air viscosity, Pa·s;
- \( \Delta p \) — pressure drop between the surface and the active area of the probe, Pa.

The air flow value is determined using the known air volume (2000 cm\(^3\)) in the sealed rubber bag and the measured evacuation time.

During the experiment, a steel hollow probe with thin diameter (12 mm) and a free pointed lower end (free tip) was driven into the soil to a depth of 0.8 m at key points (118 points in total). Using a metal core, the free tip was extruded to a certain depth. This created an active area between the soil and the probe head. The probe was connected to the RADON-JOK system using a rubber hose. To evacuate air from the formed geometry, one or two metal weights with a diameter of 60 mm and a length of 120 mm were suspended from the system, depending on the permeability of the soil. The time to fill the sealed rubber bag was recorded. The measurement was carried out at least 3–5 times. According to the developed nomographic map, the parameter of soil gas permeability was determined depending on the time of filling the sealed rubber bag.

2.3. Calculation of the Diffusion Model of Radon Transport

The main goal of calculating the model in our experiment was to confirm the leading role of rocks in the near-pipe space in the formation of radon anomalies in the territory of kimberlite magmatism. Unfortunately, when conducting field studies, we did not consider the parameters of the convective rate of radon transfer, and therefore, it was impossible to include the contribution of other factors such as fracturing at the boundary of a kimberlite pipe. Future work will expand the list of determined parameters, for example, radon radiation, soil temperature and moisture at different depths, as well as microseismic measurements to identify zones of fracturing faults. In this regard, we chose the only possible radon transport model in this study—the diffusion model described by Fick’s laws. Diffusion transfer was carried out without the application of external forces in the direction of radon radiation decrease due to the thermal motion of atoms [47]. The most important parameter in calculating the diffusion model of radon transport is the diffusion coefficient [48]. Indeed, the values of the diffusion coefficients of radon in rocks and soils depend on the permeability and porosity of the rocks, pore structures, temperature, and degree of filling of the pores with water [47]. In this work, the values of the diffusion coefficient were taken from the literature based on the physical parameters (porosity, density) of the studied rocks.
The main equation for calculating the diffusion model of radon transport in this study was the distribution function along the vertical profile of radon radiation in a homogeneous soil. This equation has the following form:

\[ C(x) = C_{Ra} \cdot K_{eM} \cdot \rho \cdot \left( 1 - e^{-\sqrt{\frac{\lambda}{D}} \cdot x} \right) \] (2)

where:
- \( C(x) \) — distribution function along the vertical profile of the radiation of “free” radon in the rock, Bq·m\(^{-3}\);
- \( C_{Ra} \) — radiation of radium-226 in the rock, Bq·kg\(^{-1}\);
- \( K_{eM} \) — coefficient of radon emanation in soil, stand. units;
- \( \rho \) — soil density, kg·m\(^{-3}\);
- \( \lambda \) — radon decay constant, 1·s\(^{-1}\);
- \( D \) — diffusion coefficient of radon in soil, m\(^2\)·s\(^{-1}\).

3. Results and Discussion

Figure 2 shows the results of field measurements of radon radiation in soil air and the gas permeability of soils in the area of the Chidvinskaya pipe. Detailed measurement results are in Appendix A (Table A1).

3.1. Results of the Measurements of Radon Radiation and Gas Permeability

The radon radiation in the soil air in the area of the Chidvinskaya pipe varies in the range from 123 to 4650 Bq·m\(^{-3}\), with an average value of 1010 Bq·m\(^{-3}\). The spatial distribution of radon over the pipe area is uneven. The highest values of radon radiation, exceeding 1600 Bq·m\(^{-3}\), are observed at the border of the pipe with the host sediments. The western, eastern, and northern borders are characterised by increased radon radiation (Figure 2). This may be due to the fact that, at the contacts of the Chidvinskaya pipe with the host Ediacaran rocks, fractured fault zones with increased gas permeability are developed, leading to the formation of the observed positive anomalous radon radiation in the soil air. The general orientation of the Ediacaran sedimentary rocks is near-horizontal; however, on the border of the kimberlite pipe and host rocks, there are local tectonic elements, namely, zones of mylonites, steep cracks, and low-amplitude thrusts. Fracturing is associated with the diatreme formation process, which influenced the tectonic structure of the adjacent sediments. As a result of this disturbance, a system of radial and concentric fracture zones was formed, with crushing and weak vertical movement of blocks of the country rocks. This affected the radiation parameters of the host rock, including the formation of radon and its vertical migration to the surface. The study of the deep structure of the Chidvinskaya pipe using microseismic measurements confirmed the presence of fault zones and fractures at the contact of the pipe with the host Ediacaran sedimentary rocks, which were distinguished in the microseismic field studies by reduced velocities [49]. The southern border of the pipe has no radon anomalies. This is due to the large thickness of the overlying sediments in this part of the pipe. Above the pipe, the variations in radon activity are insignificant and do not exceed 1200 Bq·m\(^{-3}\). The gas permeability of rocks in the area of the Chidvinskaya pipe vary from \(0.1 \times 10^{-13}\) to \(110 \times 10^{-13}\) m\(^2\), with an average value of \(6.2 \times 10^{-13}\) m\(^2\). A comparison of the distribution of radon radiation with the distribution of the gas permeability parameter showed that areas with increased values of radon radiation and gas permeability coincided partially (Figure 2). However, areas with the highest radon radiation do not reflect the distribution field of the gas permeability parameter. This is likely due to the fact that an increase in the thickness and composition of the overlying sediments can reduce the permeability of soils and does not allow the gas permeability parameter for a pipe using the RADON-JOK system to be determined reliably.

The results of the correlation analysis show no relationship between radon radiation and permeability (Figure 3). The correlation coefficient is 0.024 and the regression coefficient
is 0.0006. If abnormally high values of permeability (over $10^{-12}$ m$^2$) are excluded, a weak relationship between these parameters is observed, with a correlation coefficient of 0.41 and a regression coefficient of 0.17 (Figure 4). These results show the need to consider multiple environmental factors (moisture and temperature, density and porosity along the soil profile, atmospheric parameters in the case of a non-stationary observation mode) in statistical analyses and the search for more complex relationships between these. The RADON-JOK system revealed the possibility of its application in assessing the radon potential in general for the territory of the kimberlite pipe, but only as an additional method and only in the case of a low thickness of the overlying Quaternary layer.

![Figure 3. Graph of the dependence of the soil permeability parameter and radon radiation.](image)

![Figure 4. Graph of the dependence of the soil permeability parameter and radon radiation (abnormal permeability values excluded).](image)

3.2. Results of the Calculation of the Diffusion Model of Radon Transport

In previous work [23], we calculated the main radiation and physical parameters of rocks that comprise a typical kimberlite field of the Arkhangelsk diamondiferous province:
overlying sediments, rocks from exocontacts of kimberlite pipes, tuffaceous–sedimentary rocks of the pipe crater, and diatreme kimberlites. Table 1 shows the ranges of the studied parameters and their average values. Additionally, we calculated the radiation and physical parameters for the sandstones with siltstone interlayers of Ediacaran sedimentary rocks using the algorithms and methods given in [23]. Due to the lack of data on the rates of radon convection, we used a diffusion model for a homogeneous and single-layer object to calculate the transfer rate. Due to the small thickness of the overlying Quaternary sediments (Q, Figure 1) in the northern part of the Chidvinskaya pipe, we did not take into account their effect on the radon radiation in the calculation. Therefore, only one layer was included in the calculation for each vertical profile. In addition, we did not consider the time factor, so the model was calculated in a stationary mode. The diffusion coefficient (D) was derived from the literature [47] in accordance with the physical parameters of the studied samples. To calculate the transport model, we used the average values of radium-226 activity (ARa226), the emanation coefficient ($K_{emanation}$), and rock density (Density).

Table 1. Radiation and physical characteristics of the samples.

| Radiation and Physical Characteristics, Range/Mean | ARa226 | $K_{emanation}$ | Density | D      |
|--------------------------------------------------|--------|-----------------|---------|--------|
| Kimberlites, D$_3$-C$_2$                         | 12.42–31.46 | 1.76–10.67   | 1.74–2.35 | $7.0 \times 10^{-6}$ |
| Country rocks, V$_2$                            | 16.05–63.32 | 6.19–29.13   | 1.47–2.19 | $4.5 \times 10^{-6}$ |
| Sandstones with siltstone interlayers, V$_2$    | 12.45–21.4  | 11.82–24.13  | 1.01–1.41 | $1.0 \times 10^{-6}$ |

Figure 5 shows the vertical distributions of radon radiation in the studied rock profiles, calculated according to Equation (2), for three profiles: pipe, country rocks, and sandstones with siltstone interlayers of Ediacaran sedimentary rocks. The actual depth of the Chidvinskaya kimberlite pipe exceeds 400 m from the surface. Considering the diffusion coefficient, the radon radiation values reached an equilibrium state after eight metres. Variations in radon in the surface atmospheric air, due to its low radiation level, do not affect the diffusion process at the soil–atmosphere boundary. Therefore, at the edge point of transfer at $x = 0$, the radon radiation in the atmosphere was regarded as zero [47].

Despite some assumptions and a general simplification of the model, the calculated results clearly show that the country rocks had the greatest potential for increased radon radiation and, accordingly, the formation of radiation anomalies. The calculated values of the radon radiation produced by the near-pipe rocks exceeded 9000 Bq m$^{-3}$. A small amount of radon was also produced by diatreme kimberlites; this calculated value of radon radiation for diatreme kimberlites with average radiation and physical parameters was at a level of 2500 Bq m$^{-3}$.

Future work will be carried out in order to determine the velocities of movement of radon along the three above-mentioned profiles. We will determine the velocities of the movement of radon on the basis of the radiation and physical characteristics of the pipe rocks, as well as the values of radon radiation at different depths. This will allow the peculiarities of the geological structure of the kimberlite body to be considered, for example, the zones of fractures and faults at the boundaries of the pipe, when calculating the already convective model of vertical radon transport along the rock mass.
4. Conclusions

Using the example of the Chidvinskaya pipe, field and experimental studies were carried out to identify the main factors influencing the formation of the radon field over the kimberlite pipes of the Arkhangelsk diamondiferous province in order to develop emanation methods for the search for kimberlite pipes. Field measurements were acquired to determine the radon radiation in the soil air and the gas permeability of soils in the area of the Chidvinskaya pipe.

We showed that the highest values of radon radiation are at the border of the pipe with the host sediments. This is likely due to the fact that fractured fault zones with increased gas permeability are developed at the exocontacts of the pipe, leading to the formation of the observed anomalous radon radiation in the soil air. At the same time, the large thickness of the overlying layer can reduce the radon flux to the surface of the earth. A comparison of the distribution of radon radiation with the distribution of the gas permeability parameter showed that areas with increased radon radiation and gas permeability partially coincided, which could be associated with an increased thickness of the overlying sediments, as well as their composition.

Based on a set of field and experimental data, a model of the diffusion transfer of radon in the area of the Chidvinskaya pipe was calculated for three profiles: kimberlite, country rocks, and sandstones with siltstone interlayers of Ediacaran sedimentary rocks. The results of the calculations show that the rocks of the exocontacts of the pipe had the greatest potential for increased radon radiation. The calculated values of the radon radiation produced by these rocks exceeded 9000 Bq m$^{-3}$ at equilibrium. The maximum radon radiation of these rocks could, however, reach 50–100 kBq m$^{-3}$. The least amount of radon was produced by the diatreme kimberlites. It was established that pipe lithology exocontacts were the source of the increased values of radon radiation observed in the soil air. The results obtained allow us to recommend the emanation method as an additional method for the search for kimberlite pipes or for mineral exploration. This method in
combination with gamma-spectrometric, seismometric, and magnetometric methods has high potential for application in geology and geophysics. Its advantages are ease of use and low cost, as drilling into the bedrock is not required.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

Appendix A

Table A1. Values of radon radiation and permeability in the territory of the Chidvinskaya kimberlite pipe.

| Sample_ID | Geographical Coordinates | Radon Radiation, Bq m⁻³ | Gas Permeability, m² |
|-----------|--------------------------|--------------------------|----------------------|
|           | Longitude     | Latitude    |                             |                        |
| ChD-1     | 41.10004      | 64.93589    | 690 ± 207                  | 3.9                   |
| ChD-2     | 41.10083      | 64.93764    | 908 ± 272                  | 4.9                   |
| ChD-3     | 41.10253      | 64.93986    | 1381 ± 414                 | 7.9                   |
| ChD-4     | 41.10343      | 64.93393    | 1117 ± 335                 | 4.2                   |
| ChD-5     | 41.10412      | 64.94156    | 1554 ± 466                 | 8.9                   |
| ChD-6     | 41.10412      | 64.93658    | 1475 ± 442                 | 4.2                   |
| ChD-7     | 41.10523      | 64.93817    | 1702 ± 511                 | 5.0                   |
| ChD-8     | 41.1059       | 64.94047    | 1524 ± 457                 | 8.0                   |
| ChD-9     | 41.10624      | 64.94331    | 1861 ± 558                 | 15.1                  |
| ChD-10    | 41.10684      | 64.93636    | 1616 ± 484                 | 4.0                   |
| ChD-11    | 41.10767      | 64.94554    | 1283 ± 385                 | 20.5                  |
| ChD-12    | 41.10809      | 64.94179    | 2918 ± 875                 | 5.5                   |
| ChD-13    | 41.1088       | 64.93776    | 1976 ± 593                 | 4.0                   |
| ChD-14    | 41.10905      | 64.94734    | 1126 ± 338                 | 7.2                   |
| ChD-15    | 41.10937      | 64.93356    | 1001 ± 300                 | 3.2                   |
| ChD-16    | 41.10995      | 64.94909    | 1468 ± 440                 | 2.9                   |
| ChD-17    | 41.11036      | 64.94338    | 193 ± 58                   | 110.0                 |
| ChD-18    | 41.11076      | 64.94527    | 134 ± 40                   | 1.2                   |
| ChD-19    | 41.11149      | 64.95084    | 1895 ± 569                 | 13.0                  |
| ChD-20    | 41.11181      | 64.93525    | 783 ± 235                  | 3.9                   |
| ChD-21    | 41.1122       | 64.94154    | 723 ± 217                  | 4.0                   |
| ChD-22    | 41.11221      | 64.93929    | 2484 ± 745                 | 5.4                   |
| ChD-23    | 41.11265      | 64.94711    | 1309 ± 393                 | 1.3                   |
| ChD-24    | 41.11282      | 64.94893    | 1480 ± 444                 | 2.0                   |
| ChD-25    | 41.11345      | 64.94342    | 964 ± 289                  | 13.9                  |
| ChD-26    | 41.1135       | 64.9528     | 2828 ± 848                 | 5.0                   |
| ChD-27    | 41.11365      | 64.93727    | 127 ± 38                   | 4.5                   |
| ChD-28    | 41.1146       | 64.95053    | 1542 ± 463                 | 4.5                   |
| Sample_ID | Geographic Coordinates | Radon Radiation, Bq m⁻³ | Gas Permeability, m² |
|-----------|------------------------|--------------------------|---------------------|
| ChD-29    | 41.11525 64.94878      | 1606 ± 489               | 5.5                 |
| ChD-30    | 41.11536 64.95439      | 3742 ± 1123              | 5.1                 |
| ChD-31    | 41.11541 64.93324      | 123 ± 37                 | 4.9                 |
| ChD-32    | 41.11571 64.9447       | 1531 ± 459               | 1.3                 |
| ChD-33    | 41.11616 64.94196      | 1810 ± 543               | 0.6                 |
| ChD-34    | 41.11616 64.95168      | 3286 ± 986               | 7.5                 |
| ChD-35    | 41.11631 64.93833      | 653 ± 196                | 2.6                 |
| ChD-36    | 41.11722 64.93523      | 135 ± 41                 | 6.0                 |
| ChD-37    | 41.11747 64.95308      | 4645 ± 1394              | 5.0                 |
| ChD-38    | 41.11785 64.95662      | 970 ± 291                | 2.5                 |
| ChD-39    | 41.11792 64.94843      | 245 ± 74                 | 1.3                 |
| ChD-40    | 41.11817 64.95079      | 2832 ± 850               | 9.1                 |
| ChD-41    | 41.11823 64.94646      | 124 ± 37                 | 1.5                 |
| ChD-42    | 41.11881 64.94061      | 784 ± 235                | 1.4                 |
| ChD-43    | 41.11897 64.93096      | 156 ± 47                 | 4.5                 |
| ChD-44    | 41.11928 64.9546       | 3401 ± 1020              | 6.2                 |
| ChD-45    | 41.11948 64.94379      | 517 ± 155                | 1.5                 |
| ChD-46    | 41.12003 64.93658      | 289 ± 87                 | 4.1                 |
| ChD-47    | 41.12062 64.94984      | 2822 ± 847               | 21.0                |
| ChD-48    | 41.12072 64.95609      | 2546 ± 764               | 3.5                 |
| ChD-49    | 41.12082 64.95259      | 2661 ± 798               | 8.0                 |
| ChD-50    | 41.12087 64.93302      | 141 ± 42                 | 5.1                 |
| ChD-51    | 41.12167 64.93907      | 468 ± 140                | 3.2                 |
| ChD-52    | 41.12246 64.94547      | 650 ± 195                | 1.4                 |
| ChD-53    | 41.12258 64.94718      | 240 ± 72                 | 1.3                 |
| ChD-54    | 41.12261 64.93463      | 147 ± 44                 | 5.4                 |
| ChD-55    | 41.12307 64.94166      | 205 ± 62                 | 1.8                 |
| ChD-56    | 41.12313 64.95067      | 877 ± 263                | 1.9                 |
| ChD-57    | 41.12415 64.95401      | 763 ± 229                | 0.3                 |
| ChD-58    | 41.12441 64.95343      | 187 ± 56                 | 0.7                 |
| ChD-59    | 41.12448 64.95588      | 1150 ± 345               | 4.0                 |
| ChD-60    | 41.12469 64.93743      | 1045 ± 314               | 5.0                 |
| ChD-61    | 41.12496 64.93075      | 172 ± 52                 | 1.9                 |
| ChD-62    | 41.12531 64.94328      | 1160 ± 348               | 1.3                 |
| ChD-63    | 41.12601 64.93566      | 1497 ± 449               | 6.0                 |
| ChD-64    | 41.12602 64.95185      | 422 ± 127                | 0.9                 |
| ChD-65    | 41.12638 64.9489       | 312 ± 94                 | 1.3                 |
| ChD-66    | 41.12665 64.93976      | 1051 ± 315               | 3.3                 |
| ChD-67    | 41.12704 64.93346      | 358 ± 107                | 2.9                 |
| ChD-68    | 41.12739 64.93705      | 1405 ± 422               | 5.4                 |
| ChD-69    | 41.12787 64.92915      | 165 ± 50                 | 2.0                 |
| ChD-70    | 41.12808 64.94489      | 2209 ± 663               | 1.7                 |
| ChD-71    | 41.12846 64.9414       | 880 ± 264                | 1.9                 |
| ChD-72    | 41.12851 64.95556      | 372 ± 112                | 9.2                 |
| ChD-73    | 41.12853 64.94698      | 241 ± 72                 | 1.3                 |
| ChD-74    | 41.12884 64.95269      | 1151 ± 345               | 2.1                 |
| ChD-75    | 41.12975 64.94231      | 483 ± 145                | 1.1                 |
| ChD-76    | 41.13015 64.9308       | 161 ± 48                 | 1.9                 |
| ChD-77    | 41.13023 64.95033      | 305 ± 92                 | 1.0                 |
| ChD-78    | 41.13069 64.93437      | 275 ± 83                 | 2.6                 |
| ChD-79    | 41.13111 64.95325      | 378 ± 113                | 80.0                |
| ChD-80    | 41.13147 64.94025      | 1026 ± 308               | 1.7                 |
| ChD-81    | 41.13161 64.93839      | 278 ± 83                 | 1.7                 |
| ChD-82    | 41.13169 64.94533      | 765 ± 229                | 0.5                 |
| ChD-83    | 41.13172 64.94844      | 364 ± 109                | 1.5                 |
| ChD-84    | 41.13282 64.95083      | 136 ± 41                 | 2.5                 |
| ChD-85    | 41.13302 64.93271      | 191 ± 57                 | 1.8                 |
Table A1. Cont.

| Sample_ID | Geographic Coordinates | Radon Radiation, Bq m$^{-3}$ | Gas Permeability, m$^2$ |
|-----------|------------------------|-------------------------------|------------------------|
|           | Longitude | Latitude  |                            |                        |
| ChD-86    | 41.13312  | 64.9554  | 460 ± 138                  | 8.5                    |
| ChD-87    | 41.13391  | 64.93607 | 131 ± 39                   | 1.8                    |
| ChD-88    | 41.13461  | 64.94649 | 684 ± 205                  | 0.1                    |
| ChD-89    | 41.13478  | 64.94374 | 935 ± 281                  | 1.9                    |
| ChD-90    | 41.13514  | 64.95333 | 1257 ± 377                 | 27.6                   |
| ChD-91    | 41.1354   | 64.93472 | 408 ± 122                  | 1.5                    |
| ChD-92    | 41.13545  | 64.93751 | 1421 ± 426                 | 1.8                    |
| ChD-93    | 41.13589  | 64.94921 | 610 ± 183                  | 1.4                    |
| ChD-94    | 41.13606  | 64.93981 | 1136 ± 341                 | 1.6                    |
| ChD-95    | 41.1372   | 64.9449  | 679 ± 203                  | 1.2                    |
| ChD-96    | 41.13736  | 64.93679 | 852 ± 256                  | 1.2                    |
| ChD-97    | 41.13747  | 64.95492 | 1523 ± 457                 | 18.1                   |
| ChD-98    | 41.13754  | 64.94715 | 1002 ± 301                 | 1.9                    |
| ChD-99    | 41.13786  | 64.94144 | 151 ± 45                   | 1.1                    |
| ChD-100   | 41.13846  | 64.95261 | 2410 ± 723                 | 6.5                    |
| ChD-101   | 41.13858  | 64.9388  | 606 ± 182                  | 1.0                    |
| ChD-102   | 41.13942  | 64.94336 | 148 ± 44                   | 1.0                    |
| ChD-103   | 41.14017  | 64.94082 | 250 ± 75                   | 0.8                    |
| ChD-104   | 41.14038  | 64.94848 | 1210 ± 363                 | 2.5                    |
| ChD-105   | 41.14066  | 64.95013 | 2071 ± 621                 | 18.0                   |
| ChD-106   | 41.14067  | 64.94468 | 749 ± 225                  | 1.9                    |
| ChD-107   | 41.14134  | 64.95476 | 1376 ± 413                 | 16.5                   |
| ChD-108   | 41.14176  | 64.94262 | 350 ± 105                  | 0.9                    |
| ChD-109   | 41.14246  | 64.94621 | 811 ± 243                  | 1.8                    |
| ChD-110   | 41.14314  | 64.95213 | 457 ± 137                  | 15.0                   |
| ChD-111   | 41.14335  | 64.94421 | 437 ± 131                  | 0.8                    |
| ChD-112   | 41.14412  | 64.94807 | 243 ± 73                   | 0.9                    |
| ChD-113   | 41.14489  | 64.94538 | 372 ± 112                  | 0.7                    |
| ChD-114   | 41.14579  | 64.95084 | 401 ± 120                  | 9.5                    |
| ChD-115   | 41.14638  | 64.95391 | 376 ± 113                  | 15.6                   |
| ChD-116   | 41.14685  | 64.94739 | 228 ± 68                   | 0.9                    |
| ChD-117   | 41.14834  | 64.94597 | 161 ± 48                   | 5.6                    |
| ChD-118   | 41.14855  | 64.95201 | 150 ± 45                   | 7.7                    |

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