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ORIGINAL ARTICLE

Deep structure of the Verkhnetovskaya kimberlite pipe in the Arkhangelsk diamondiferous province according to passive seismic and radiological methods

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Abstract
The exploration of kimberlite pipes is difficult. However, information about their deep structure is necessary for tasks such as prospecting, exploration and development of kimberlite pipes. Therefore, it is necessary to increase the efficiency of deep structure research. In addition, pipes in different territories differ in their properties. The latter requires the study of the peculiarities of the manifestation of pipes in various areas. The Verkhnetovskaya pipe is the only kimberlite object currently known in the Chernoozerskaya area of the Arkhangelsk diamondiferous province. This indicates the need for a comprehensive study of this pipe. The main reason it is difficult to study the pipes of the Arkhangelsk diamondiferous province is the large overburden thickness. In order to increase the efficiency of prospecting, we used a set of methods: microseismic sounding method, passive seismic interferometry, H/V method, gamma spectrometry and emanation mapping. The analysis showed that a new field measurement technique was tested in this research, resulting in more stable data. The main improvement in field measurements is the determination of the optimal accumulation time of microseism when implementing the microseismic sounding method. In addition, the location of the stations in the implementation of passive interferometry made it possible to minimize the influence of the azimuthal distribution of ambient noise sources. The studies made it possible to construct the geophysical image of the investigated pipe and the surrounding medium. As a result, it was shown that the northwestern side has a vertical structure, while according to the drilling data, the side has a uniform slope. In particular, the presence of previously unknown lateral channels was shown. The proposed methodology made it possible to obtain important information with minimal time and technical costs, confirming the applicability of the proposed methodology in the Chernoozerskaya area.

KEYWORDS
gamma spectrometry, kimberlite pipe, noise, passive method, radon emanation, velocity analysis

INTRODUCTION

The Arkhangelsk diamondiferous province (ADP) in the Arctic zone of Russia is the only diamondiferous region in Europe with industrial diamond reserves (Kutinov & Chistova, 2004; Garanin et al., 2008; Verzhak et al., 2008; Zinchuk & Zinchuk, 2014). At present, more than 70 pipes have been discovered in the province, most of which are not diamondiferous. It should be noted that most of the pipes were discovered in the 1980s (Ignatov et al., 2018), and since then, there have been

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no significant discoveries of new pipes. This state of affairs endangers the reproduction of the mineral base of diamonds in Europe. Proven diamond reserves are estimated to be only 20 years old (Materials of the meeting…2017). The main method of prospecting for kimberlites was magnetic survey (Shchukina & Shchukin, 2018), since most of the province is far from roads and covered with a thick layer of terrigenous-carbonate deposits. However, to date, the pool of promising magnetic anomalies for verification by drilling is practically exhausted (Kutinov & Chistova, 2004; Verzhak et al., 2008; Stogniy & Korotkov, 2010). The methods of indicator minerals are not applicable, since the kimberlites of the ADP contain relatively few indicator minerals, particularly pyropes (Sobolev, 1991; Bogatikov et al., 1999; Kudryavtseva et al., 2004). As a result of the secondary transformation of kimberlites (saponification), light minerals occupy most of the total volume of pipes (Sobolev, 1991).

In addition, most of the pipes are weakly eroded and have a crater, which makes it difficult for indicator minerals to enter the environment (Garanin et al., 2008). Other geophysical and geochemical research methods have not yielded satisfactory results for the discovery of new kimberlite pipes (Babayants et al., 2006). In this regard, special efforts are required to develop new approaches in the search for pipes (Korotkov, 2011). One such approach in terms of prospects for industrial application is a set of passive seismic and radiometric methods tested on a number of pipes of the Arkhangelsk diamondiferous province (Danilov, 2011; Danilov et al., 2017; Kiselev et al., 2017; Frantsuzova & Danilov, 2018; Yakovlev, 2020).

In these experiments, the main passive seismic method was the microseismic sounding method (MSM) (Gorbatikov et al., 2008; Danilov, 2011). For the first time, MSM has been successfully tested on the pipes in Belarus (Gorbatikov et al., 2009). Testing the MSM on a number of ADP kimberlite bodies showed that the method allows the extraction of a tubular body at depths of up to 1.5 km. (Danilov, 2011; Frantsuzova & Danilov, 2016, 2018; Danilov et al., 2017, 2021). Different pipes were imaged as heterogeneities with different contrast. Moreover, the first phase of the introduction of the Pionerskaya pipe (Danilov et al., 2017) had not been identified. Also, problems of passive seismic interferometry were identified in the absence of a pronounced source of microseism (Danilov et al., 2017). Radiometric methods have shown that kimberlite bodies appear as contrasting radio-geochemical anomalies, formed mainly by elevated concentrations of thorium and potassium. Also, above the pipes, increased values of the volumetric activity of radon (VAR) were recorded. In addition, the anomalies of the radon field can be used to trace the heterogeneities of the geological section associated with faults and fragmentation of the host rocks. Due to the thick overburden, the radio-geochemical anomalies were inhomogeneous. Also, it is difficult to interpret the methods separately due to the complex structure of the pipes and the surrounding environment. However, the complex use of the listed methods significantly increases the reliability of the interpretation (Danilov et al., 2021).

The possibility of combining MSM and radiometric methods was tested using the example of the Chidvinskaya pipe of the Chidvinsko–Izhmozersky field of the ADP (Kiselev et al., 2017). This test showed the consistency of subvertical fractured zones with radio-geochemical anomalies and deep structure. However, the test was carried out on only one object and along a profile. A more careful study took place at the Lomonosov pipe and identified the features of the control structures and the deep structure of the pipe (Danilov et al., 2021). At the same time, different kimberlite fields have different composition, age and physical properties of pipes. As a consequence, more reliable conclusions require the continuation of verification on various pipes of the ADP. The main feature of the Verkhnetovskaya pipe is its similarity to the composition of the Griba pipe, the highest diamond-bearing pipe in the ADP (Garanin et al., 2008). That there are no other kimberlite pipes in the Chernoozerskaya area emphasizes the relevance of this work.

This paper presents the results of the investigation of the deep structure of the Verkhnetovskaya pipe studies by the proposed set of methods.

CHIDVINSKAYA PIPE

The Megorsk kimberlite field is located ∼130 km northeast of the city of Arkhangelsk and is currently represented by only one explosion pipe, Verkhnetovskaya. This pipe is the northernmost in the Arkhangelsk diamondiferous province (Figure 1).

The Megorsk field is located in the northern part of the East European platform, in the zone of its junction with the Baltic crystalline shield. This determines the presence of two structural floors. The lower structural level is a crystalline basement, represented by the Lower Archean formations with an age of 3.5 billion years and the Proterozoic with an age of 2.7 billion years (Gubaidullin, 2002). The upper structural layer is a sedimentary cover. It is divided into the Riphean, Vendian, Upper Paleozoic and Cenozoic stages (Shirobokov, 1997; Stankovsky, 1997; Kharkiv et al., 1998; Bogatikov et al., 1999). The Riphean stage combines weakly metamorphosed deposits of the Middle and Upper Riphean up to 2 km thick. The Vendian stage is represented by sandy-argillaceous deposits with a total thickness of 0.5–1.0 km. The Upper Paleozoic includes carbonate deposits of the Lower, Middle and Upper Carboniferous. A study of xenoliths of sedimentary rocks in kimberlite pipes of the M.V. Lomonosov showed that the region was represented by terrigenous-carbonate rocks of the

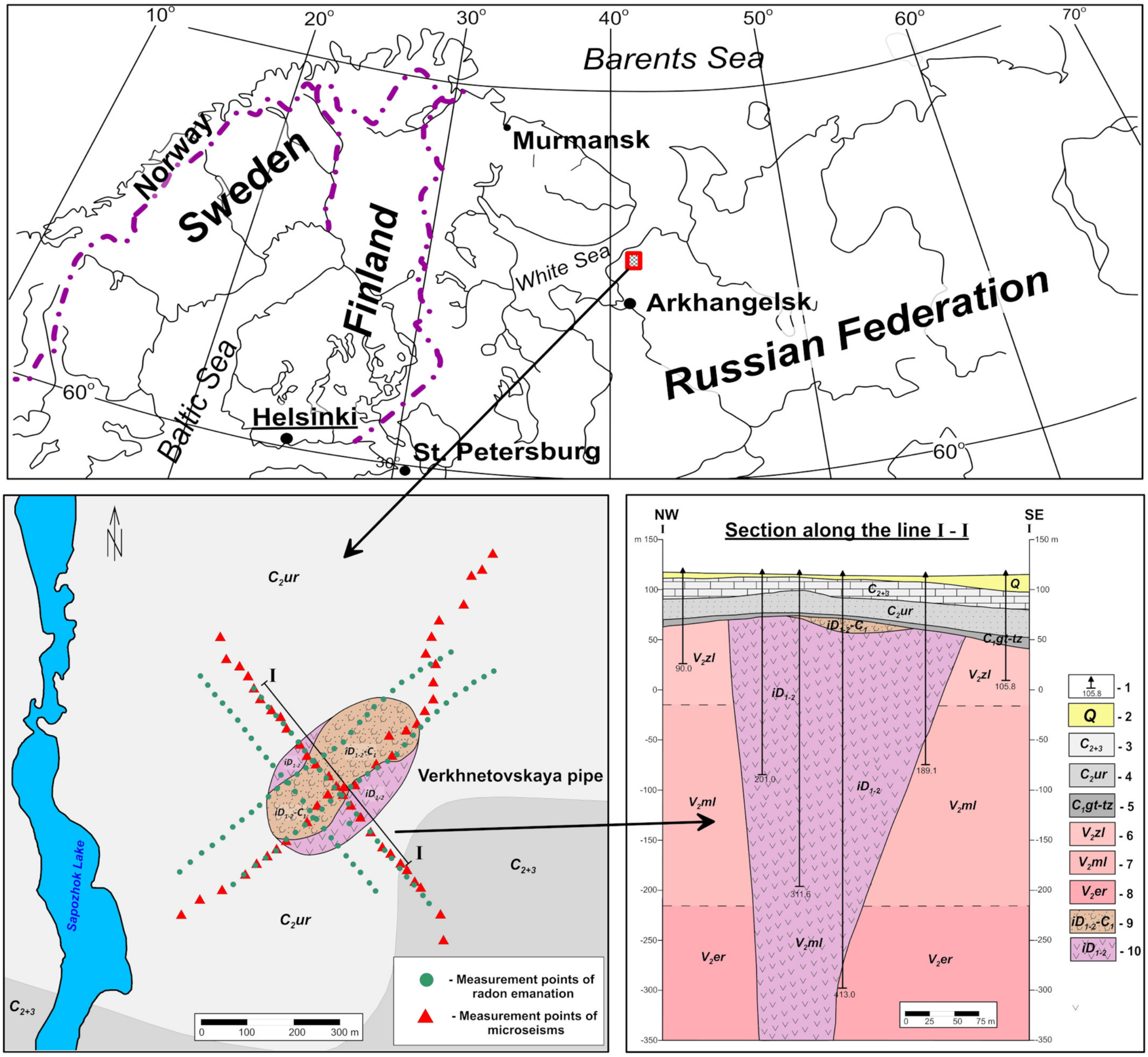


FIGURE 1 Studied area. Geological schemes of the area and the Verkhnetovskaya pipe.

Lower Paleozoic (Lower Cambrian–Lower Ordovician) with a total thickness of about 100 m (Sablukov, 1987; Zinchuk & Zinchuk, 2014).

The rocks containing the pipe to a depth of 500 metres are the deposits of the Zolotitskaya, Mel'skaya and Erginskaya formations of the Vendian, represented by interbedded siltstones, mudstones and sandstones. The overlying rocks of the pipe are represented by deposits of the Lower, Middle and Upper Carboniferous and Quaternary deposits. The Olmugsko–Okunevskaya, Urzugskaya and Telzinsko–Gruborucheyskaya formations, represented by alternating sandstones, limestones and dolomitic limestones with inclusions of cherts, are distinguished in the Carboniferous deposits in the area of the pipe. Quaternary deposits completely cover ancient rocks. Genetically, Quaternary deposits are fluvioglacial, glacial, lacustrine, boggy and alluvial deposits (Kutinov & Chistova, 2004). The predominant rocks include sand, loam, pebbles, sandy loam and peat. The thickness of the Quaternary deposit ranges from 10 to 20 m. In the buried paleovalleys, the thickness of the Quaternary deposits increases to 140 m.

In the vertical section, the Verkhnetovskaya kimberlite pipe has the shape of a typical funnel with an expansion in the upper part. The dimensions of the pipe in the plan are 410 m × 240 m, and the area is about 7.7 hectares. The vent part of the pipe is made with xenotufobreccia (iD1-2). In the upper part of the pipe, a crater composed of tuffaceous-sedimentary deposits (iD1-2-C1) has been preserved. The content of diamonds down to a horizon of −150 m is estimated at 0.003 ct/t.

METHODS

In our study, we considered the joint use of several methods: microseismic sounding (MSM) (Gorbatikov et al., 2008, 2013), passive seismic interferometry with an advanced stacking method (Afonin et al., 2019), the H/V spectral ratio method (H/V method) (Nakamura, 1989), emanation mapping (Magomedova & Udoratin, 2016) and gamma spectrometry (Babayants et al., 2006). The advantage of this set of methods is that it allows one to study the main prospecting features of kimberlite pipes, which are subvertical heterogeneities, the most contrasting horizontal boundaries, and geochemical anomalies. Below is a brief description of these methods, and a more detailed description is presented in Danilov et al. (2021).

Radon method and gamma spectrometry

Radon is a decay product in the uranium-238 chain. The background volumetric activity of radon is usually in the range from 5 to 50 kBq·m^{-3} (Danilov et al., 2021). Faults cause an increase in intensity by 1.5–3 times (Neznal et al., 1991, 1996). In view of the sufficiently long decay time of radon, the emanation method is most effective in mapping the faults, determining the width of fracture zones, evaluating the degree of tectonic activity of faults (Bobrov, 2009; Seminsky et al., 2009, 2014) and in the search for ore deposits, as emanation survey of soil air (Neznal et al., 1991).

The emanation survey is potentially useful to identify kimberlite bodies because of two factors. First, kimberlite bodies are controlled by faults (Milashev, 1979; Kutinov & Chistova, 2004). Second, fractured zones are usually located in the near-pipe space. These fractures are associated with the process of diatreme formation as a result of the significant mechanical effect of incipient gases and melts on the host rocks (Nikitin, 1980; Milashev, 1984; Khazanovich-Wulff, 2007). Consequently, diatreme magmatism creates areas of increased values of volumetric activity of radon (VAR; Khazanovich-Wulff, 2007).

Studies of the radon activity in soil sediments were carried out on kimberlite pipes of various diamondiferous provinces. Emanation studies were performed on kimberlite pipes in South and West Botswana (McDowall & Koketso, 1991) and the territory of the Chetlassky and Volsko–Vymsky uplifts of Middle Timan (Magomedova & Udoratin, 2016). These papers demonstrated the prospects of the emanation method in the prediction of kimberlite bodies. For most Arkhangelsk diamondiferous province (ADP)'s pipes, the excess of the background values of radon at the boundary with the enclosing medium was averaged four times (Kiselev et al., 2016). Due to the test nature of the initial work on each pipe of the ADP, only one profile was studied. Many volumetric activities of radon anomalies were probably related to the content of ^{226}Ra in the rocks. As a rule, higher background radon activity was observed in the areas of allocation of Medium Carboniferous carbonate deposits containing silicified interlayers with a high uranium content (for example, near the Pionerskaya pipe). On some pipes (Lomonosov, Pomorskaya, and Koltsovskaya pipes), it was difficult to distinguish one of the boundaries from the background. Thus, the data obtained allow us to associate the formation of local anomalies of radon in the soil air with zones of increased fracturing in the endo- and exocontacts of the pipes. However, to better understand the characteristics of the reflection of pipes in the field of radon activity, it is necessary to conduct more detailed areal studies on reference objects. These studies can contribute to a more complete understanding of the characteristics of the formation of a radon field in the soil air over kimberlite pipes.

The promise of gamma spectrometry for detecting kimberlite bodies was demonstrated in diamond districts in the Yakutia (Babayants et al., 2006), the Timan–Ural province (Rybalchenko et al., 2011) and Canada and India (Mwenifumbo & Kjarsgaard, 1999; Ramadass et al., 2015). There is still no clear relationship between the halos of radioactive elements in the overlying sediments and the kimberlite pipes in the ADP. The main factors that complicate the accumulation of radioactive elements in the upper horizons in ADP are complex landscape-geological conditions, the development of Quaternary fluvioglacial sediments and a humid climate with excessive moisture. Due to the low concentrations of radioactive elements in the overlying rocks, the anomalies associated with ADP's kimberlites could not be identified by the method of an airborne gamma-ray survey (Babayants et al., 2006).

However, surface gamma-spectrometric surveys using highly sensitive detectors have distinguished kimberlite pipes by anomalies of total radioactivity, mainly concentrations of potassium and thorium (Kiselev et al., 2016; Yakovlev, 2017; Danilov et al., 2021). At the same time, anomalies associated with glacial sediments of moraines, as a rule, were distinguished by high concentrations of uranium.

Passive seismic methods

The MSM is based on the proposal that the vertical component of ambient seismic noise is presented, predominantly, by the fundamental mode of Rayleigh waves. This assumption is true for natural microseismic oscillation (Bath, 1974). According to Gorbatikov et al. (2008, 2013), Gorbatikova and Tsukanov (2011), Lin et al. (2012) and Eddy and

Ekström (2014), the fundamental mode of Rayleigh wave increases its amplitude above low-velocity inhomogeneity and decreased amplitude above high-velocity inhomogeneity. The variations of intensity of microseisms were recorded on the surface, while inhomogeneity was located under the surface in some depth. Also, analysis of amplitude information allows for improving the resolution of the method in the horizontal (Gorbatikova & Tsukanov, 2011; Lin et al., 2012). The MSM does not require the medium to be layered. As a consequence, the MSM can be used in complex geological environments near kimberlite pipes.

MSM is a differential amplitude technique where measurements are conducted successively at the points of a profile. Simultaneously, the microseismic signal should be recorded at the reference point located around the studied area to apply a correction to eliminate the non-stationary sounding of the microseismic signal.

The result of the processing is the geophysical cross-section, a distribution of relative intensity of microseisms along the profile and in depth (I). Zones with a higher relative microseism intensity represent an area with relatively reduced velocity properties and vice versa. A more detailed description of the method is presented in Gorbatikov et al. (2013), Danilov (2017) and Kugaenko et al. (2018).

Passive seismic interferometry is based on the estimation of an empirical Green's function by cross-correlation or convolution of ambient noise, recorded simultaneously in different locations (Shapiro & Campillo, 2004; Wapenaar et al., 2008; Wapenaar & Draganov, 2010). This method is widely used in surface wave tomography (e.g. Shapiro et al., 2005; Yang et al., 2007; Lin et al., 2007) and body wave imaging (Poli et al., 2012) for the study of fault structure (Afonin et al., 2017) and shallow subsurface structure (Lin et al., 2013; Cheng et al., 2015; Le Feuvre et al., 2015). In our study, we used an improved method of passive seismic interferometry, which allows for decreasing time of measurement and improving quality of the obtained dispersion curve (Afonin et al., 2019). The field measurements require simultaneous records of ambient seismic noise at least in three points. It is necessary for removing the effect of the azimuthal distribution of ambient noise sources.

The H/V method allows estimating depth to the borders inside the medium by analysis of resonance frequencies of seismic noise. The method is based on the analysis of three-component seismic noise records (Ibs-von Seht & Wohlenberg, 1999; Lane et al., 2008). The field implementation of the method is very close to the MSM. Thus, the H/V method was used for receiving additional information. In particular, boundaries identified by the H/V method, as a rule, correspond to distortions of the shape and intensity of subvertical inhomogeneities observed in the result of the MSM.

Methodology improvement

The MSM sensitivity can be increased from 0.7 dB to 0.3 dB for frequencies up to 1.5 Hz by increasing the signal accumulation period from 1.5 to 4 hours (Danilov, 2017). Since the velocity of surface waves at a frequency of 1.5 Hz is approximately 400 m/s, an increase in sensitivity can be expected for depths greater than 100 m. Since the thickness of the overlying sediments of the pipes of the ADP is 50–100 m, it can be argued that an increase in the signal accumulation period makes it possible to increase the sensitivity of the method to the pipes. It should be noted that improving the quality of the seismic image is also possible by increasing the signal accumulation period when checking the instruments. The influence of these factors on the quality of the seismic image is discussed below.

DESCRIPTION OF THE FIELD MEASUREMENTS

Gamma-spectrometric studies were carried out using a high-precision mobile scintillation gamma-spectrometric complex RS-700 (Kiselev et al., 2016). The RS-700 complex has a digital spectrometer (ADS) with a high-resolution (1024 channels), which allows real-time measurements of total radioactivity in nGy/h, as well as the separate measurement of the concentration of total uranium (ppm), thorium (ppm) and potassium (wt%). The complex is equipped with a built-in GPS receiver, which allows precise binding of each measurement to time and coordinates. The complex uses the RADAssist software, which makes it possible to carry out data processing directly in the field. The measurements were carried out at the height of 0.7 m above the earth's surface in a pedestrian version according to a system of profiles over an area of 1 km^2. The distance between profiles is 100 m.

The radon survey on the Verkhnetovskaya pipe was carried out along four profiles with a step of 25 m. Two parallel profiles crossed the pipe in the SW–NE direction, and two more parallel profiles are oriented in the NW–SE direction. Measurements of the volumetric activity of radon in the soil air were carried out with an automated radon radiometer RRA-01M-03 (OOO NTM-Zashchita, Russia). The relative measurement error does not exceed 30% at a confidence level of 0.95. To measure the volumetric activity of radon in the soil air, pits were drilled to a depth of 0.8 m using a manual soil drill. A gas receiver with a volume of 0.046 L was lowered into the formed cavity and held to equalize the radon concentration in the soil air and in the volume of the sampler. Several numbered gas receivers were used to speed up radon measurements. Immediately after removing the gas receiver, the soil gas was pumped into the ionization chamber of the radon radiometer using a built-in blower with a capacity of 1.0 ± 0.3 L/min for five minutes. Then radon-222 was measured in a gas receiver. In total, 109 measurements of radon volumetric activity were carried out during the fieldwork.

To implement the passive interferometry method, the signal was accumulated at four points at the edges of the study area. The distance between the stations was from one-half to 1 km. The microseismic signal was recorded simultaneously by all stations during the day. This configuration made it possible to provide the size of the Fresnel zone of 45 degrees, which leads to an error in determining the speed of 40%.

For the H/V and microseismic sounding methods, measurements were made along two profiles crossing the pipe from the southwest to the northeast and from the northwest to the southeast (Figure 1). These profiles coincided with two radon profiles but went out at a greater distance from the pipe. At each point, microseismic vibrations accumulated over three hours, and the reconciliation time was five hours. The distance between the points was 30 m. The registration of microseisms was carried out simultaneously by the mobile and reference stations. The reference station was located near the intersection of the profiles.

RESULTS

Results of passive seismic methods

According to the results of the microseismic sounding method (MSM; Figure 2c and d), a high-velocity tubular body of a conical shape with its apex facing down was identified. The horizontal position of this body confidently coincides with the investigated pipe indicated by dashed lines, but the absolute values of the depths are twice as high. This suggests that the obtained dispersion is characterized by the apparent velocities of surface waves. Also, the influence of the nonstationarity of microseisms, which also increases the error, cannot be ruled out. For convenience in describing the results, we will operate with depths determined from the results of the experiment.

According to the MSM results, the pipe is surrounded by vertical faults. The faults can be traced from a depth of 100 m to 2000 m. Faults are more localized at the profile directed from the northwest to the southeast. It can be assumed that the faults are directed mainly along the first profile in a northeastern direction.

The more consolidated block of the host medium is identified from the northeast of the pipe. This is the only area in which the intensification of microseisms is less than in the pipe. It can be assumed that this part is located outside the fault zone that controls the kimberlite pipe.

Distortions of vertical faults are observed at depths of 450–500 m. The lateral channels of the pipe in the southeast and northwest directions are distinguished at the same depths (Figure 2c and d). These channels are not identified from the drilling data. The channel in the southeastern direction is traced to the edge of the profile over a length of 250 m and slightly approaches the surface as it moves away from the pipe. The lateral channel in the northwest direction does not have a distinct exposure to the surface and can be traced to a distance of 100–150 m from the pipe. It can be assumed that the exposure to the surface occurred from the northwest of the pipe away from the MSM profiles and was observed as a high-velocity anomaly at the second profile. Drilling was performed only in the immediate vicinity of the pipe and, was most likely located in the low-velocity zone adjacent to the northwestern flank of the pipe. Thus, the presence of the lateral channel and its exposure to the surface is acceptable.

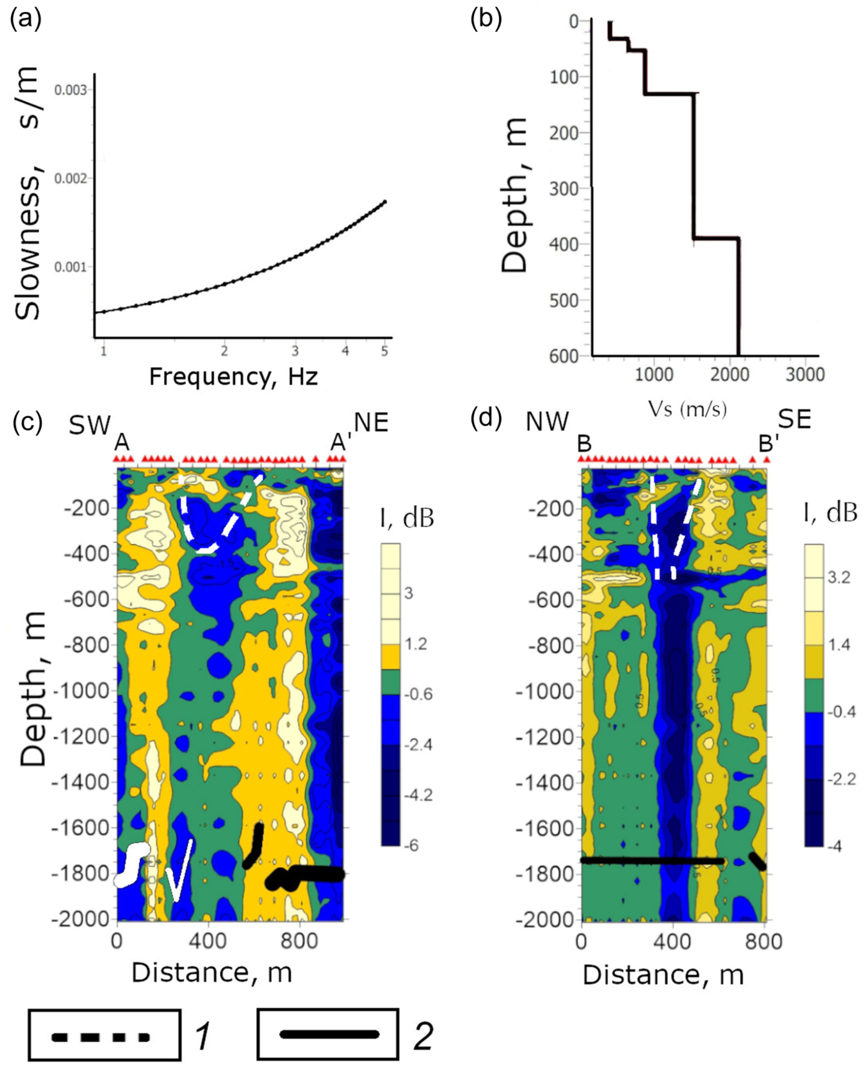
According to the data of the second profile, the narrowing of the pipe body with depth is imaged locally and only up to a depth of 400 m. Deeper than the level of the lateral channel directed to the southeast, there is a stepwise expansion of the pipe to the size of the pipe on the surface. Deeper than the level of the lateral channels, the root of the pipe has a vertical structure.

The southern flank of the pipe is almost vertical. Expansion of the pipe body as it approaches the surface occurs mainly in the northeast direction from a depth of 1000 m. The predominant expansion in the northern direction is also noted according to drilling data (Figure 1). The main difference from the drilling data is that, according to the MSM, the northwest side has a vertical structure, while, according to the drilling data, the side has a uniform inclination. This disagreement is most likely due to a sparse network of wells and a high density of microseismic recording points.

The greatest distortion of the vertical zones identified according to the MSM data is observed at a depth of 1800 m. At the same depth, the boundary is distinguished according to the H/V method indicated by continuous lines. It should be noted that within the vertical faults, the boundary identified by the H/V method is highly complicated. The boundary is the most contrasting in the high-speed block on the first profile. This fact indicates the reliability of the interpretation of the identified areas as faults and a consolidated block.

According to the data of passive seismic interferometry, dispersion characteristics were obtained, and a velocity model of the studied medium was constructed (Figure 2a and b). The velocity model identifies layers at depths of 30 m, 50 m, 130 m and 400 m. Nevertheless, according to the carat data (Popov, 1988), the boundaries should correspond to depths of 15 m, 25 m, 65 m and 200 m, which are accurately two times shallower than obtained. The first three correspond to the lower boundaries of the upper, upper-middle and middle sections of the Carboniferous deposits. The last boundary can be attributed to the boundary inside

FIGURE 2 Results of passive seismic methods. Dispersion curve of fundamental mode of Rayleigh waves (a) and S-waves velocity model (b) calculated according to passive seismic interferometry. Geophysical cross-section according to the microseismic sounding method with boundaries according to the H/V method (continuous lines) and pipe boundaries according drilling data (dashed lines) (c, d).



the pipe. Taking into account that recorded surface waves, used for evaluation of dispersion curve, distributed both inside the pipe and host medium, obtained dispersion curve contains some average velocity characteristic of pipe and host medium. Therefore, the obtained disagreements on depths could be caused by a strong contrast between mechanical properties (seismic velocities and densities) of pipe and host medium.

Influence of the signal accumulation period on the quality of microseismic sounding method results

In Danilov (2017), it was shown that the sensitivity of MSM increases with an increase in the signal accumulation period up to four hours. However, an infinite increase in accuracy by increasing the accumulation period is not possible due to the nonstationarity of microseisms (Gorbatikov & Stepanova, 2008; Danilov, 2017). The Verkhnetovskaya pipe is suitable to check the influence of this factor since in the medium under study, there are both contrasting and low-contrast inhomogeneities (Figure 2c and d). Processing with different accumulation periods was performed to check the influence of this factor on the results of MSM. A comparison of the results (Figure 3) shows that an increase in the signal accumulation period improves the quality of the seismic image.

The signal accumulation period of one hour (Figure 3a and d) allows identifying only faults. The body of the pipe looks low-contrast. Also, local anomalies appear on the section. As a result, it is difficult to reliably interpret the high-velocity inhomogeneity as a pipe. The fault zones can be reliably judged only when it appears in a number of adjacent points.

When the signal accumulation period is two hours, the conical shape of the explosion pipe was imaged (Figure 3b and e). The number of local linear anomalies in the sections has significantly decreased. Heterogeneities form a more consistent pattern. The clearest seismic image is observed for depths of up to 400 m, which corresponds to frequencies more than 0.8 Hz.

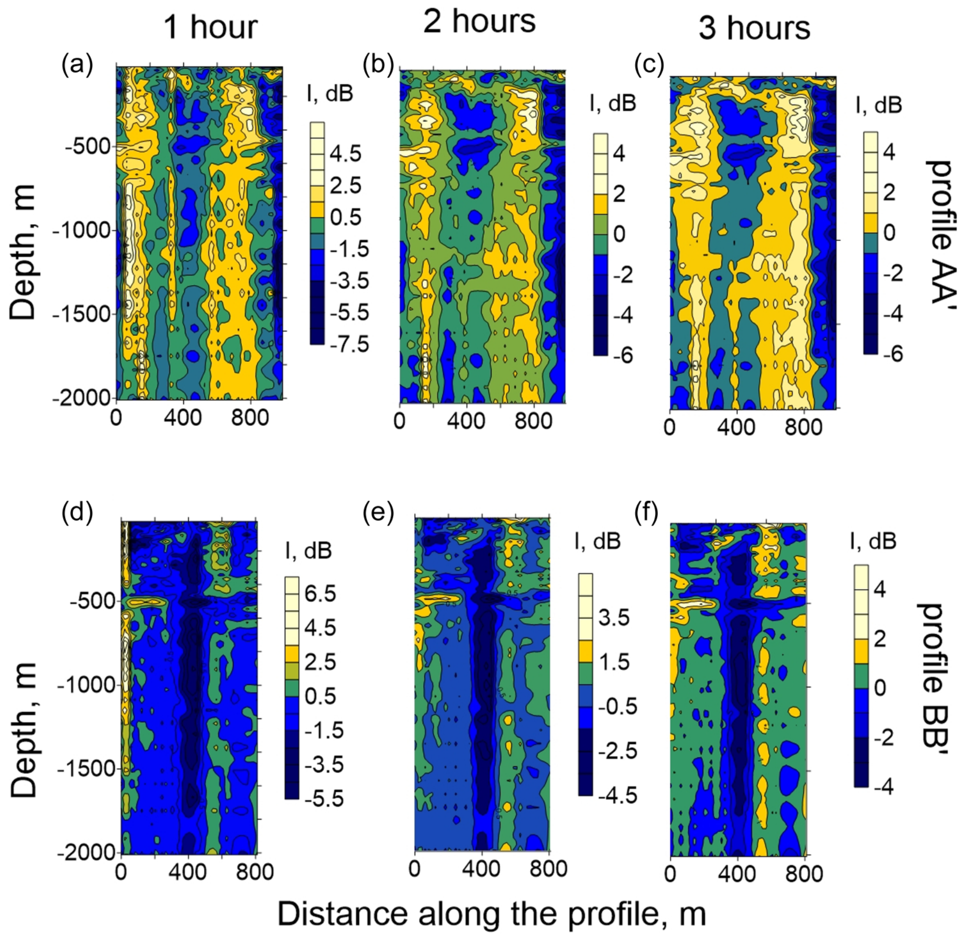


FIGURE 3 Results of processing according to the microseismic sounding method with different accumulation periods of measurements.

The seismic image becomes the most contrasting when the signal is accumulated for three hours (Figure 3c and f). The fault zones and the pipe body are clearly identified. The clearest seismic image is observed for depths of up to 1500 m, which corresponds to frequencies more than 0.5–0.6 Hz.

The signal accumulation period of verifying the instruments also affects the quality of the results (Figure 4). However, the influence is less than in the case of the signal accumulation period during measurements. Nevertheless, an increase in the accumulation period to five hours made it possible to significantly reduce the influence of linear narrow vertical zones and significantly increase the contrast of heterogeneities.

Radon method and gamma spectrometry

According to the results of the ground-based gamma-spectrometric survey, a zone of increased radioactivity of rocks overlapping the pipe was identified (Figure 5). This zone extends from northeast to southwest, which corresponds to the direction of the kimberlite-controlling fault identified by the results of MSM (Figure 2). The most contrasting halo of total gamma activity is observed above the pipe and has a sub-concentric shape. The total gamma activity in this area ranges from 20 to 42 nGy/h, with background values averaging about 10 nGy/h. The distribution pattern of potassium over the pipe is generally similar to the distribution of total gamma activity. The potassium concentration forms a halo above the pipe with a concentration of 1.3%–4.7%, with background values of 0.6%–1.0%. Thorium concentration ranges from <2 to 25 ppm. The area with high concentrations of thorium is confined to the pipe and stretches from northeast to southwest. Uranium is more complexly distributed. There are a large number of isolated uranium halos with concentrations of 2–6 ppm not associated with the pipe (Figure 5). It is likely that a large number of false uranium anomalies are observed due to the complex landscape-geological conditions in the study area caused by the development of fluvioglacial Quaternary deposits. Thus, the most informative signs of the pipe are total gamma activity, potassium and thorium content.

The field of increased values of the volumetric activity of radon in the soil is formed above the pipe. Thus, values of volumetric activity of radon above the pipe are from 500 Bq/m^3 to 6000 Bq/m^3 (Figure 6). The maximum value

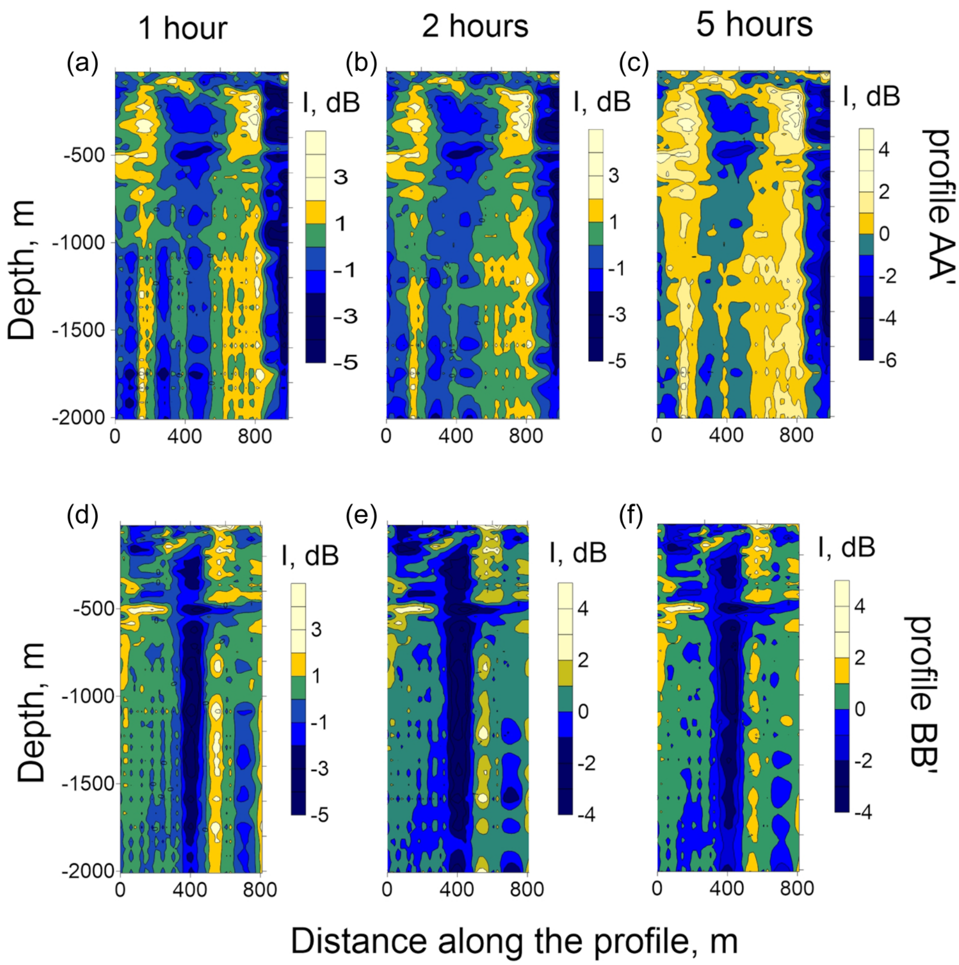


FIGURE 4 Results of processing according to the microseismic sounding method with different accumulation periods of verifying the instruments.

observed over the boundary separating the crater and vent of the pipe is probably due to the development of fracturing section tuffaceous-sedimentary deposits of the crater and on the borders.

DISCUSSION

The results of different methods are consistent with each other. The shape of the pipe body and its horizontal position reconstructed from the microseismic sounding method (MSM) correspond to the drilling data. The results of radiometric studies made it possible to establish that its projection on the surface is an oval. Thus, the combination of the proposed methods makes it possible to more confidently extrapolate deep sections in space.

According to the results of MSM and gamma spectrometry, a number of faults were identified. At the same time, only the kimberlite-controlling fault was imaged as linear anomalies of the total gamma activity. This fact can serve as an additional search feature. It is possible that tracing this fault will open up new kimberlite pipes.

The predominant expansion of the pipe body in the northeast direction can be explained by the strike of the ore-controlling fault. Thus, as it approached the surface, it was easier for kimberlite to expand along the strike of the fault due to its lower density and increased fragmentation. In the northwest and southeast directions, the pipe flanks are practically vertical with lateral channels. Probably, these channels were formed as a result of the propagation of kimberlite in a more porous layer, followed by the release of kimberlite to the surface along the adjacent fault zones (Figure 2d). This assumption is indirectly confirmed by the fact that the root zone below the lateral channel is much wider than the pipe body above the lateral channel.

According to the MSM data, the lateral channels are identified at the same depth as the change in the velocity properties according to the data of passive seismic interferometry. It is fair to assume that the lateral channels formed in the intermediate layer between the two formations. Also, the lateral channels are confidently manifested according to the data of the flow of potassium and volumetric activity of radon. According to the volumetric activity of radon data, only the lateral channel in the northwest direction was identified since

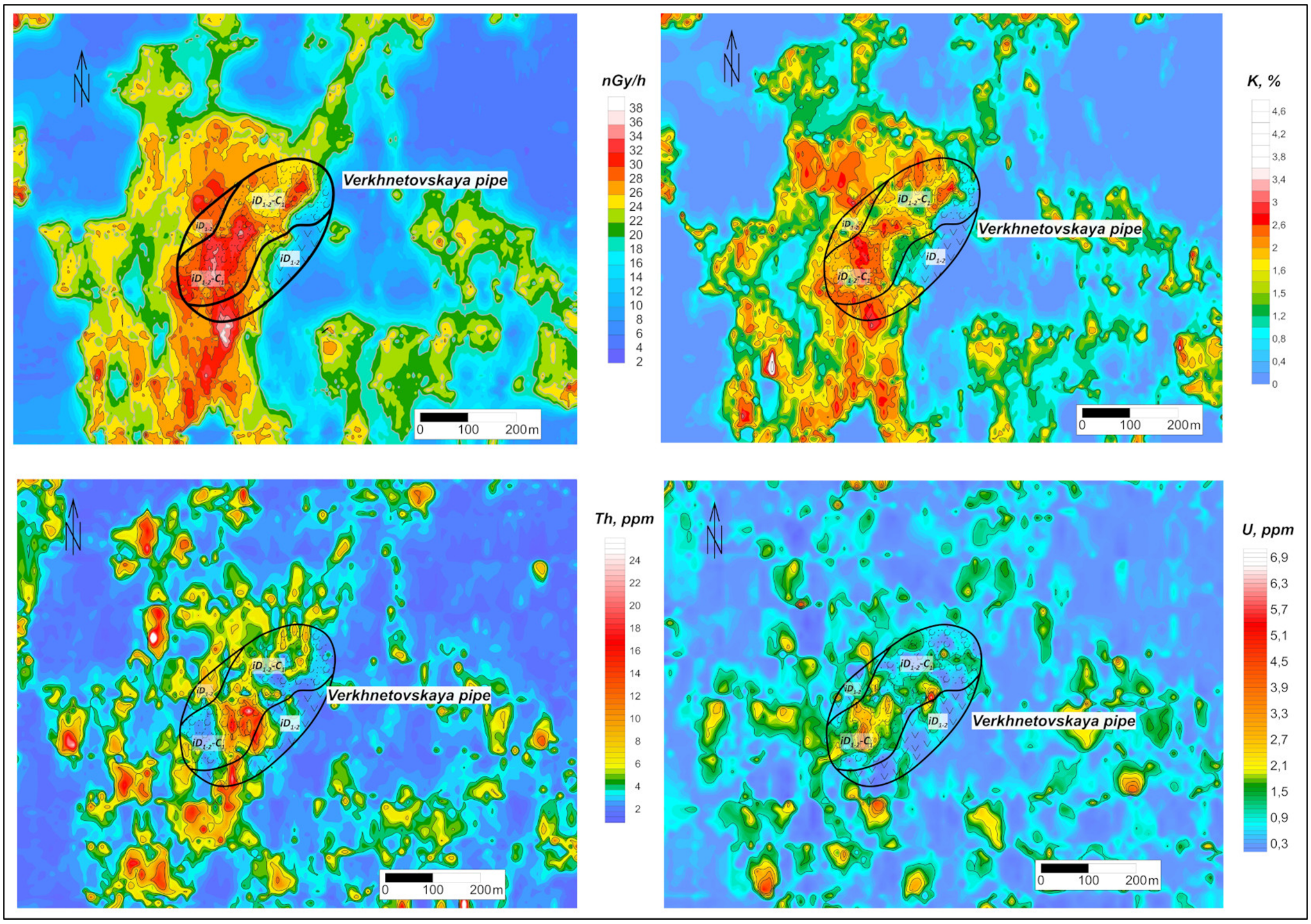


FIGURE 5 The distribution of total radioactivity, concentration of thorium, potassium and uranium over the Verkhnetovskaya kimberlite pipe.

it most fully coincided with the volumetric activity of the radon measurement profile. The presence of an anomaly in the total gamma activity south of the end of the second profile indicates that this channel approached the surface south of the MSM profile. Thus, the work carried out has established the presence of previously unknown lateral channels. Additional areal studies will make it possible to more accurately determine the position of the lateral channels.

Interestingly, the explored Verkhnetovskaya pipe has a higher velocity than faults and a lower velocity than the consolidated medium. A similar conclusion was noted earlier for the pipe named after M.V. Lomonosov (Danilov, 2011; Frantsuzova & Danilov, 2016). This fact can be explained by the fact that the solidified heterogeneous rocks of the pipes have more high velocities than faults but lower velocities than homogeneous blocks of the earth's crust. The pipes of the Lomonosovskoye deposit, Pomorskaya and Lomonosov, as well as the Verkhnetovskaya pipe, are well manifested in the fields of potassium and thorium and do not manifest themselves at all in the concentration of uranium. Thus, the listed parameters are stable prospecting features of kimberlite bodies in various kimberlite fields of the Arkhangelsk diamondiferous province.

CONCLUSION

The proposed set of methods—microseismic sounding method (MSM), passive seismic interferometry, H/V method, gamma-spectrometric and radon surveys—made it possible to obtain a high-quality image of the studied environment at relatively low costs. As a result, the pipe body and the controlling fault were identified. Thus, it has been shown that the proposed set of methods can be successfully applied in the search and study of pipes in the Chernoozerskaya area of the Arkhangelsk diamondiferous province (ADP).

The Verkhnetovkaya pipe is identified as a high-velocity cone-shaped body with an anomaly in the total gamma activity and volumetric activity of radon.

The first stable prospecting features of kimberlite bodies in various kimberlite fields of the ADP are increased values of potassium and thorium. The second is the ratio of the velocity properties: pipes have a higher velocity than faults and a lower velocity than the consolidated enclosing medium.

The kimberlite-controlling fault manifested itself as a linear anomaly in gamma-ray activity and low velocities.

The presence of two previously unknown lateral channels of the pipe was shown.

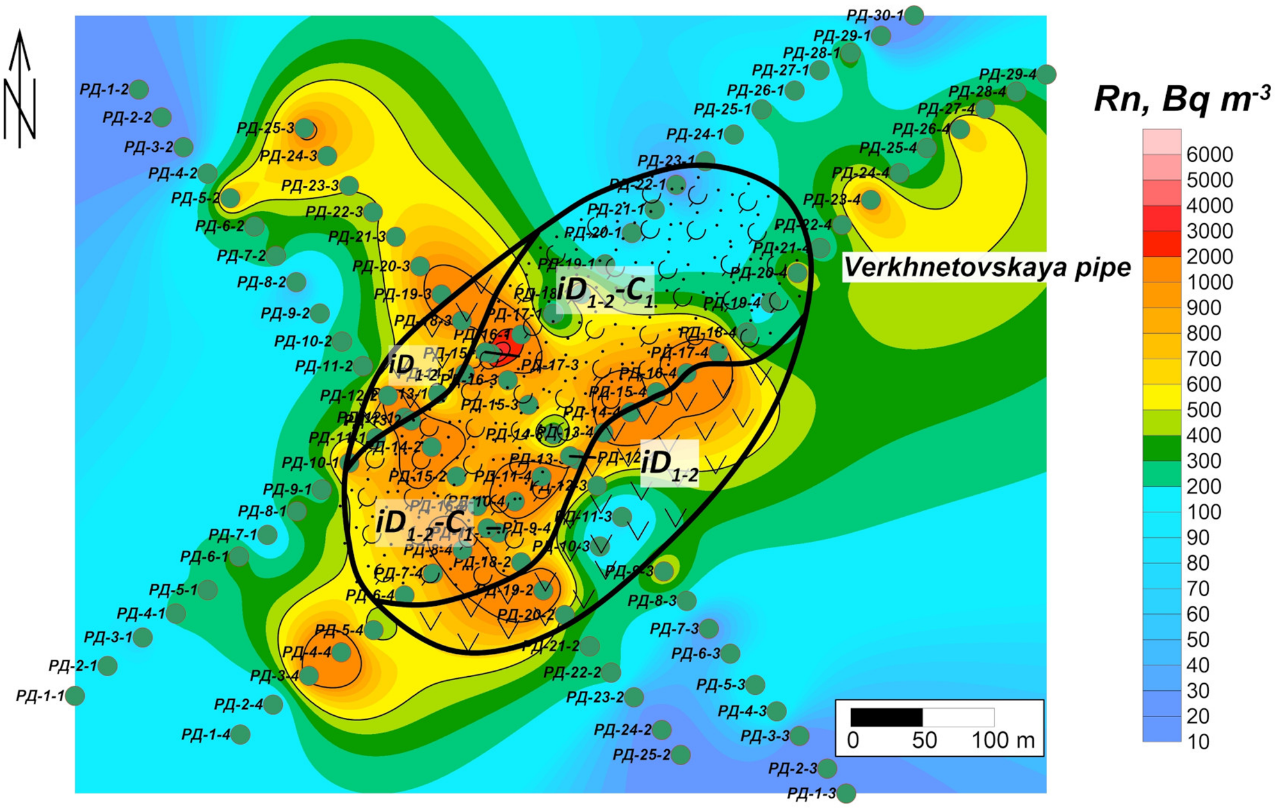


FIGURE 6 Distribution of volumetric activity of radon in soil gas near the Verkhnetovskaya kimberlite pipe.

For confident pipe identification according to the MSM, it is necessary to accumulate a signal for three hours.

The main drawback is that the depth of the identified heterogeneities was twice as large as the actual data. The reason for this error, most likely, is the distribution of the wavefield in a strong heterogeneous medium. Nevertheless, it is effective only on results of dispersion curve inversion (not on results of MSM and HV).

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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