

CHARACTERISTICS OF THE DEEP STRUCTURE OF THE KIMBERLITE-CONTROLLING FAULTS OF THE ARKHANGELSK DIAMONDIFEROUS PROVINCE ACCORDING TO THE MICROSEISMIC SOUNDING METHOD. REVIEW

K. B. Danilov* 

N. Laverov Federal Centre for Integrated Arctic Research of the Ural Branch of the Russian Academy of Sciences, Arkhangelsk, Russia

* **Correspondence to:** Konstantin Danilov, danilov_kostea@mail.ru.

Abstract: Prospecting for kimberlite pipes can be challenging due to their small size in plan. One potential solution to this problem is to search for kimberlite-controlling faults. In addition, information on the depth structure of kimberlite-controlling faults is important for studying pipe formation patterns. However, this approach is rarely used in practice due to the complex structure of the host environment. This issue is particularly pressing in areas where there is a large layer of rocks overlying the pipes, such as the Arkhangelsk diamondiferous province. The paper presents a review of the host environment structure of pipes in the Arkhangelsk diamondiferous province using the microseismic sounding method. The method was selected for its high horizontal resolving power, which enabled us to obtain more detailed information. The study reveals that the controlling structures consist of a sequence of vertical elementary faults that traverse the entire thickness of the Vendian sedimentary cover and extend into the crystalline basement. Additionally, the controlling structures do not penetrate above the Ust-Pinezhskaya formation of the Vendian sediments when at a distance from the pipes. Shear wave velocities within these faults are reduced by more than two times compared to the undisturbed medium. The pipes are interconnected with one of the elementary faults. Therefore, the method of microseismic sounding can confidently identify kimberlite-controlling structures in a complex host medium. Further application of these results could enhance the efficiency of both the search for new deposits and the study of the patterns of formation of pipes.

Keywords: Microseisms, Velocity analysis, Passive method, Faults, Kimberlite pipe.

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1. Introduction

Kimberlite fields occupy territories of tens of square kilometers. However, the pipes themselves have dimensions ranging from tens of meters to a few kilometers [Milashev, 1984; Stogniy and Korotkov, 2010]. The small size of these prospecting objects in relation to the entire territory significantly complicates the discovery of new deposits. Diamond deposits are characterised by their complex geological structure and poorly contrasted prospecting features [Gubaidulin, 2001; Stogniy and Korotkov, 2010; Ustinov et al., 2022]. In the Arkhangelsk diamondiferous province (ADP), prospecting of pipes is further complicated by a thick overlying layer, which reduces the contrast of kimberlite bodies in potential fields. Furthermore, the thick layer of sediment contains numerous “false” objects that have geophysical images similar to the search object. These factors significantly reduce the efficiency of prospecting works, both during the implementation of geophysical methods and drilling stages. Currently, there is a sharp decrease in the efficiency of prospecting [Stogniy and Korotkov, 2010]. To increase the efficiency of diamond deposit development, it

is necessary to introduce new approaches to prospecting pipes. One promising direction for improving efficiency is analyzing controlling faults.

The pipes are characterized by their cone-shaped structure with the top facing downwards [Milashev, 1984] and their confinement to the intersection of faults [Stogniy and Korotkov, 2010]. Previous studies have demonstrated that the cone-shaped structure of pipes and the host environment's structure are reliably detected through the microseismic sounding method (MSM). The main advantage of MSM over other geophysical methods is its ability to allocate subvertical objects. Additionally, the method's results are not affected by “false” objects [Danilov et al., 2021, 2022; Frantsuzova and Danilov, 2016; Gorbatikov et al., 2009], which significantly increases the informativeness of the study of the host environment.

Previously, the application of MSM on pipes revealed several faults in the host environment. Additionally, MSM enabled the reconstruction of detailed images of the complex host environment. It is important to note that the reliability of MSM test results on the pipes was confirmed by drilling, which allows for confident interpretation of information about the host environment. The reliability of each result in particular is discussed in a series of relevant articles. Therefore, the obtained results can be considered for further analysis [Danilov et al., 2021, 2022; Frantsuzova and Danilov, 2016; Gorbatikov et al., 2009]. Determining the features of manifestation of controlling faults by MSM can increase the efficiency of prospecting for pipes. However, in the past, the host environment of each pipe was analyzed separately. To identify consistent features, a more in-depth analysis of the results is required. Therefore, this paper reviews the features of the host environment based on MSM data.

2. Objects of Research

This paper analyses five pipes shown in Figure 1: the Lomonosov [Danilov et al., 2021; Frantsuzova and Danilov, 2016] and Pionerskaya [Danilov et al., 2017] – both part of the Lomonosov deposit, Chidvinskaya pipe of Chidvinsko-Izhmozerskoe field [Kiselev et al., 2017], C10 pipe of Nenokskoe field [Frantsuzova and Danilov, 2016], and Verkhnetovskaya pipe of Verhotinskoe (Megorskoe) field [Danilov et al., 2022]. As a result, the objects under consideration cover the majority of the kimberlite and melilite-pecrite fields in the province. The respective publications for each pipe provide a detailed description of the study objects. Below is a description of the faults that control the ADP pipes.

In the Late Devonian-Middle Carboniferous, formation of a submeridional system of ore-controlling deep faults and intensive magmatic activity occurred in the ADP territory, which is associated with the formation of pipes of alkaline-ultrabasic (kimberlites, melilitites) and basic (tholeiitic basalts) compositions. This emplacement coincided with the global manifestation of alkaline magmatism of the Kola Peninsula. The Zolotitskoye and Melskoye kimberlite fields, the Verkhotinskoye and Kepinskoye kimberlite and melilitite fields, the Izhmozerskoye and Nenokskoye melilitite fields, and the Turyinskoye, Poltinskoye, and Pinezhskoye basalt fields are distinguished based on their spatial distribution and material composition [Bogatikov et al., 1999].

The structural criterion requires that pipes be confined to fault zones. Geological and geophysical studies have identified two types of fault zones. The first type has a wide zone of deformed rocks but insignificant vertical displacement amplitude. The second type consists of faults that form broad grabens [Kalinin, 1989]. Only fault zones of the first type are identified in this paper. Accordingly, this discussion will focus on the first type of fault zone. These zones are typically complex, wide (1.5–2 km), and extended structures that include several elementary faults [Kalinin, 1989]. A zone of this type was identified within the Lomonosov deposits based on seismic data [Kalinin, 1989] shown in Figure 2 and electrical exploration [Stogniy and Korotkov, 2010] shown in Figure 3. Based on seismic and electrical survey data, the fault zone is identified as a complex heterogeneity. However, reliable identification of elementary faults was not possible.

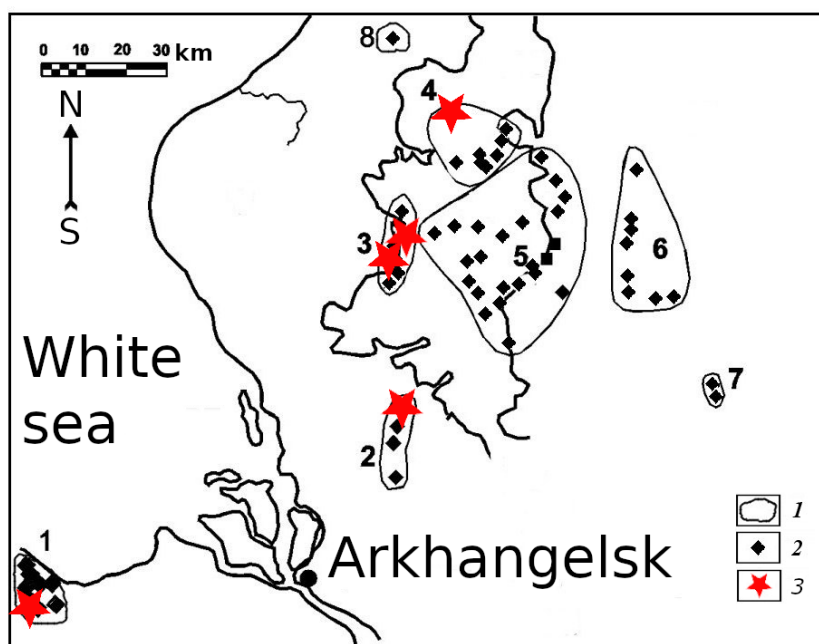


Figure 1. Scheme of the distribution of igneous rocks of the Arkhangelsk diamondiferous province [Tretyachenko *et al.*, 2013] with addition. 1 – kimberlite fields; 2 – explosion tubes; 3 – pipes examined using microseismic sounding. (1 – Nenokskoe, 2 – Izhmozerskoe, 3 – Zolotitskoye, 4 – Verkhotinskoye, 5 – Kepinskoye, 6 – Turinskoye, 7 – Poltinskoye, 8 – Melskoye).

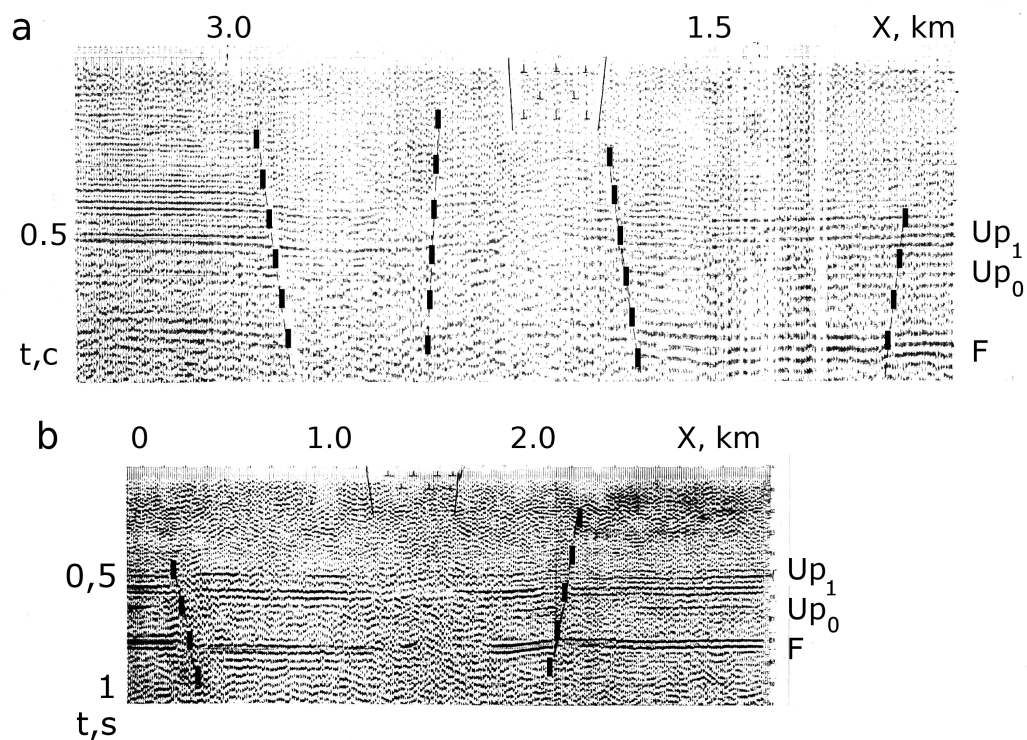


Figure 2. Common Depth Point Method time sections highlighting fault zones (shown in dotted lines) in areas where kimberlite pipes were introduced [Kalinin, 1989]. a – Snegurochka pipe; b – Pionerskaya pipe. F, Up₀, Up₁ are reflected waves characterizing the surface of the crystalline basement and two boundaries in the Ust-Pinega formation, respectively.

Seismic studies have shown that the integral value of P -wave velocities in the first type of fault zones is 3–5% lower than in normal conditions. Elementary faults are sub-vertical discontinuities with a width of several tens of meters, likely consisting of three sub-zones: abrasion, compression, and physical property alteration. It is important to note that the elementary faults that constitute the controlling structures have not been reliably investigated [Kalinin, 1989].

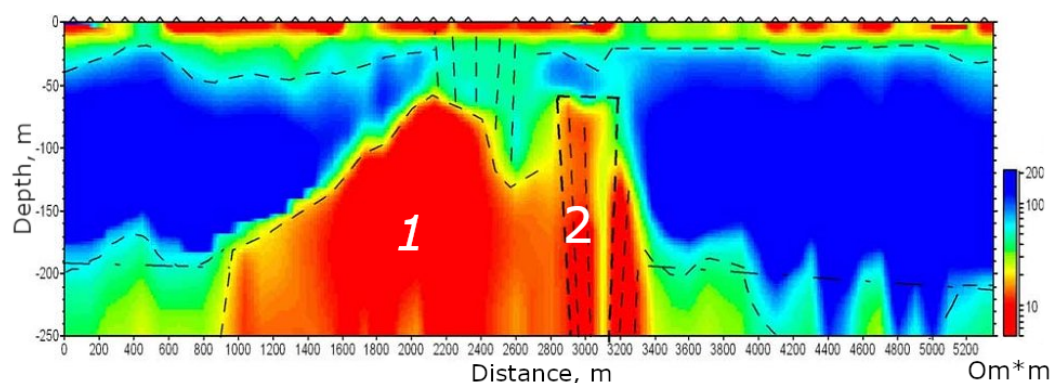


Figure 3. Goelectric section through the kimberlite-controlling fault (1) and the Lomonosov pipe (2) Lomonosov kimberlite pipe [Stogniy and Korotkov, 2010].

The Arkhangelsk diamondiferous province 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 [Gubaidulin, 2001]. The upper structural layer is a sedimentary cover. It is divided into the Riphean, Vendian, Upper Paleozoic, and Cenozoic stages [Bogatikov et al., 1999; Shirobokov, 1997; Stankovsky, 1997]. 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. 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 Lower Paleozoic (Lower Cambrian-Lower Ordovician) with a total thickness of about 100 m [Sablukov, 1987].

On the pipes of the Zolotitskoe kimberlite field, the tectonic signs of the near-pipe space in the form of faults and fractures are clearly distinguished. This aspect has been studied most thoroughly on the Arkhangelskaya pipe, because this pipe is developed by a quarry. On other pipes of the Zolotitsky field, tectonic features of the near-pipe space are recorded in the cores of exploration wells [Ignatov et al., 2009]. Thus, local tectonic elements accompanying the exocontacts of kimberlites are revealed in the Arkhangelskaya pipe [Ignatov et al., 2008, 2012]. The pipe is bounded by the zones of mylonites and steeply dipping fractures, including low-amplitude overfaults and subsidence faults. Tectonic disturbances are accompanied by enclosing and overburden deposits and are reliably determined in the Urzugskaya Carboniferous and Padunskaya Vendian suites [Vasilyev, 2010]. Endogenous vein lightening develops along these fracture zones. The dimensions of the spreading aureole of secant clarification reach the diameter of the pipe and are fixed along the perimeter of the near-contact space, both directly on the tectonic contacts of the crater part of the pipe, as well as at up to 300 m from the pipe. The lightening develops along the cracks and has a thickness of up to 20 cm [Ignatov et al., 2015].

3. Microseismic Sounding Methods

The most contrasting changes in physical properties in the first type of fault zones are expected in the abrasion subzone of elementary faults [Kalinin, 1989]. In the abrasion zone it is fair to expect a decrease in the shear modulus. Consequently, the abrasion

subzone have the most contrasting effect on transverse wave velocities. One of the effective methods for studying such structures is the microseismic sounding method [Gorbatikov, 2006; Gorbatikova and Tsukanov, 2011].

The microseismic sounding method (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 [Eddy and Ekström, 2014; Gorbatikov et al., 2008, 2013; Gorbatikova and Tsukanov, 2011; Lin et al., 2012], 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 and 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. On the other hand, the method will not allow us to identify horizontal layering without significantly changing the depth of the layers. Besides, it is necessary to control a quality of signal at preliminary conduction. In particular, at high frequency signal can be distorted by man-made source.

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. 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 [Danilov et al., 2017; Gorbatikov et al., 2013; Kugaenko et al., 2018].

Measurements were made along profiles crossing the pipes. Also considered are sublatitudinal profiles from the north of the Lomonosov pipe, at a distance of 50 m and 1 km. The distance between microseism measurement points varied from 30 to 70 meters. The signal accumulation period ranged from 1.5 to 3 hours. The profiles ranged in length from 0.8 to 2.8 km. This paper considers sublatitudinal profiles crossing the Lomonosov, Chidvinskaya and C10 pipes. Submeridional profiles crossing the Lomonosov and Pionerskaya pipes are also considered.

4. Theoretical Valuation

According to the results of mathematical modeling [Gorbatikov et al., 2013; Gorbatikova and Tsukanov, 2011], the MSM allows to identify objects with dimensions of about 0.07 of their depth with a horizontal resolution of about 0.6 of the depth. Considering that fault zones have a width of 1–2 km, we can assume that they can be identified down to depths of 15–30 km, i.e. practically across the entire thickness of the Earth's crust. However, this requires profiles of 60 km or more in length. Elementary faults probably have a characteristic width of 50 m and can therefore be identified to depths of 700 m. And their shape and size can be studied to depths of 100 m.

It is important to note that it is reasonable to expect a “super-resolution” effect of the MSM in the abrasion subzone of the elementary fault. *In this case, the resolution becomes close to the minimum size of heterogeneity identification.* This effect has been described in the study of an extinct volcano and confirmed by the results of mathematical modelling [Gorbatikov et al., 2013]. As a result, it is reasonable to expect that elementary faults can be traced to depths of 1 km and more. The spacing between measurement points for reliable identification of elementary faults should be less than the resolution of the method at the depths investigated and comparable to the width of the faults, which is 30–50 meters.

The thickness of the sedimentary cover in the studied areas is 1–2 km. Thus, for the Lomonosov, Pionerskaya and Verkhnetovskaya pipes, the thickness is 700–900 m [Danilov et al., 2021, 2022]. This is consistent with previously published data [Baluev et al.,

2012; Gubaidulin, 2001]. For the C10 and Chidvinskaya pipes, the thickness ranges from 1 to 2 km [Baluev et al., 2012]. In summary, it is reasonable to expect that the available data will allow us to analyse the entire sedimentary cover. In addition, in case of super-resolution effect, it is possible to study elementary faults.

5. Results

The structure of the host medium is known for the Lomonosov, Pionerskaya, Pionerskaya, Chidvinskaya, Verkhnetovskaya and C10 pipes by the microseismic sounding method (MSM) shown in Figure 1 [Danilov et al., 2017, 2021, 2022; Frantsuzova and Danilov, 2016]. This set of pipes covers the majority of the ADP kimberlite fields. At the same time, the most information is available for the Lomonosov and Pionerskaya pipes as they are part of the Lomonosov diamond deposit. The Lomonosov pipe has been studied in the most detail using the MSM method. As such, the data for it are known along the sublatitudinal and submeridional profiles, as well as along the sublatitudinal profiles at 50 m and 1 km north of the Lomonosov pipe. Therefore, more attention is paid to the Lomonosov and Pionerskaya pipes.

5.1. Lomonosov and Pionerskaya Pipes

According to microseismic data shown in Figures 4 and 5, the Lomonosov and Pionerskaya pipes appear as low-velocity inhomogeneities. At the same time, blocks with properties close to those of the host medium are found inside the pipes. In all cases, the pipes appeared in the form of a deformed cone with the apex pointing downwards at depths up to 2 km [Danilov et al., 2021, 2022; Frantsuzova and Danilov, 2016]. In this respect, the qualitative character of the pipe contrast with respect to the host medium is not a stable feature.

Contrasting faults are highlighted in the host medium to the west of the Lomonosov pipe shown in Figure 4a. In Figure 4a these anomalies are numbered 1–3. The pipe itself corresponds to anomaly number 4. These faults form a series of linear vertically contrasting low velocity anomalies at depths greater than 2 km with anomalies approximately 50–200 m wide. All of the highlighted faults have a contrast of up to 16 dB. According to the results of mathematical modeling [Gorbatikov et al., 2013], this contrast may be due to a decrease in velocity by more than a factor of two. The tracking of these anomalies to depths of more than 1 km with almost no blurring indicates that they are due to the effect of “super-resolution” [Gorbatikov et al., 2013]. The presence of the “super resolution” effect suggests that the observed anomalies could have been generated by sub-zones of abrasion of elementary faults. It is interesting to note that the most contrasting narrow and extended disturbance is highlighted in close proximity to the pipe.

Further investigation of the Lomonosov pipe has shown that it is located directly on top of an elementary fault, as reported by [Danilov et al., 2021]. This fault exhibited a contrast from the north of the pipe and was less distinct from the south. Similar observations were made for the Verkhnetovskaya pipe [Danilov et al., 2022].

Based on the submeridional profiles crossing the Lomonosov and Pionerskaya pipes shown in Figure 4b, no linear vertical faults were detected. Pipes had less contrast. The lack of linear faults may be attributed to the co-direction of the profiles and controlling faults. It is worth noting that, at a depth of approximately 500 m, the root section of the pipe appears to have shifted towards the north. At depths between 500 and 1000 meters, the pipe root is associated with the low-velocity zone of the sedimentary cover located to the south of the pipe. Additionally, a low-velocity zone has been identified to the north of the Lomonosov pipe. It is likely that these low-velocity zones are caused by controlling faults.

Figure 5 presents a comparison of three sublatitudinal profiles: one crossing the Lomonosov pipe, another located north of 50 m from the pipe, and a third located north of 1 km from the pipe. The comparison confirms the continuation of the highlighted fault system northward for at least 1 km. The selected strike of the controlling structures

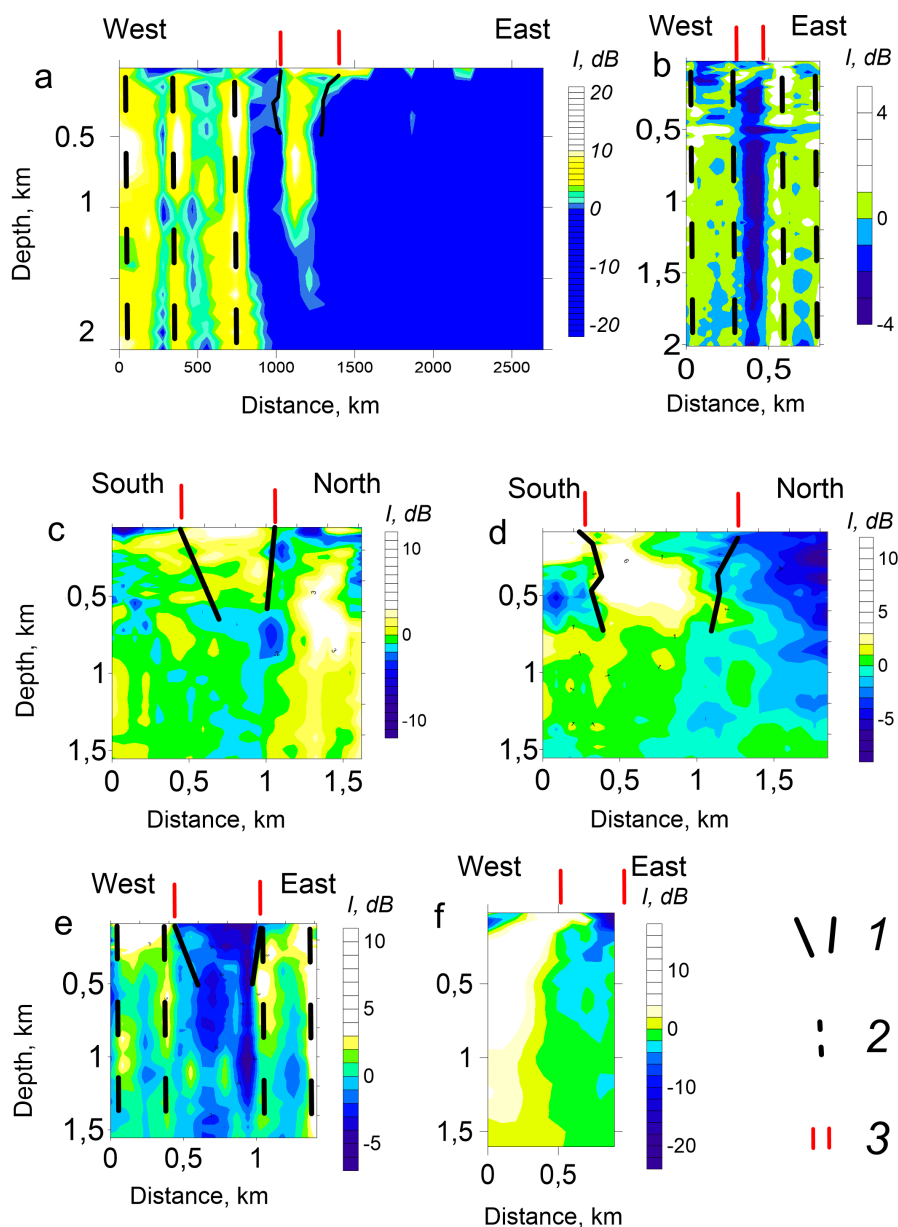


Figure 4. Results of data processing along profiles crossing the explosion pipes: a – Lomonosov [Frantsuzova and Danilov, 2016]; b – Verhnetoskaya [Danilov et al., 2022]; c – Lomonosov ; d – Pionerskaya [Danilov et al., 2017]; e – Chidvinskaya [Kiselev et al., 2017]; f – C10 [Popov et al., 2014]; 1 – boundary of pipes and intrusion phases according to drilling data; 2 – identified linear vertical heterogeneities according to the microseismic sounding method; 3 – boundaries of pipes on the surface.

coincides with the results of electrical exploration [Stogniy and Korotkov, 2010], which confirms the reliability of the results. It is worth noting the uniform distribution of linear faults. Thus, the average distance between the faults is about 200 m.

We also see from Figure 5 that the elementary faults penetrate to varying depths, all of which are deeper than 1 km. These faults cross the Vendian deposits of the sedimentary cover and continue into the crystalline basement, where the depth is 700–900 m. It is possible that the faults penetrate deeper, but their small size makes them indistinguishable at such depths. At depths greater than 4 km, a number of faults can be confidently distinguished. It is reasonable to assume that these faults can also be traced at even greater depths, indicating the potential for conducting deeper studies.

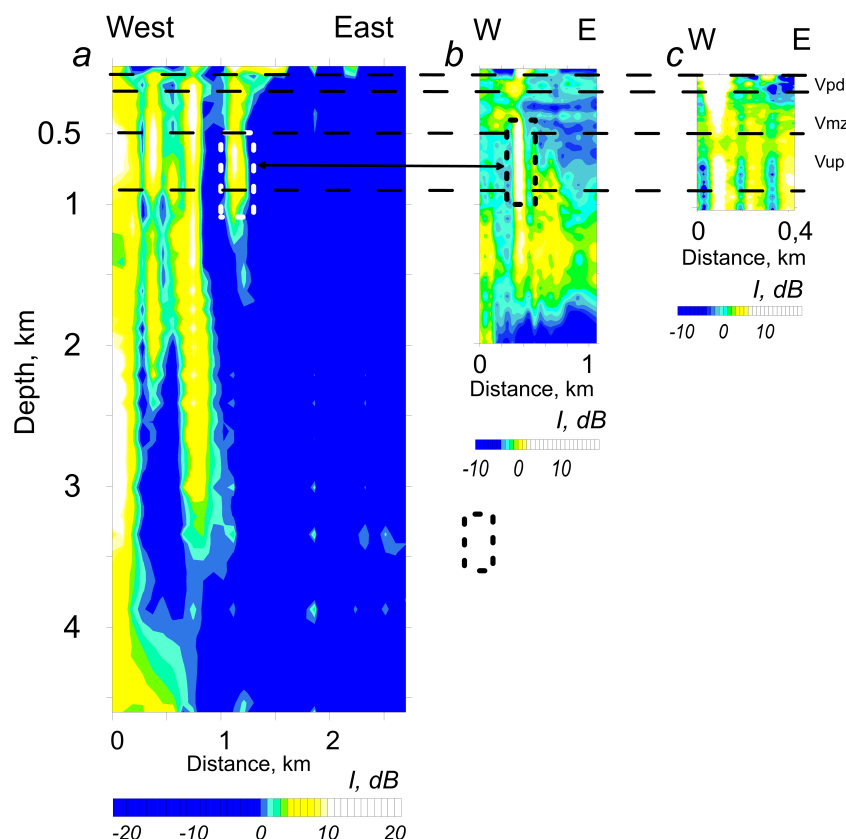


Figure 5. Structures controlling the Lomonosov pipe according to MSM data along the profiles: a – crossing the Lomonosov tube; b – 50 m north of the pipe [Danilov et al., 2022]; c – 1 km north of the tube; 1 – elementary fault controlling the pipe; 2 – identified anomalies. Vpd, Vmz, Vup–Vendian suites, respectively Padunskaya, Mezenskaya and Ust-Pinezhskaya.

At a distance of 1 km from the Lomonosov pipe, elementary faults were observed at depths greater than 400 m. When in close proximity to the pipe, elementary faults are observed at depths of 100 m, with the maximum contrast also located at depths of 400 m to 1000 m. Depths greater than 400 m correspond to the Ust-Pinezhskaya Formation of Vendian sediments. Figure 6 shows that the upper boundary of the control zone, as identified by the MSM data near the pipe, is in agreement with the results of electrical exploration [Stogniy and Korotkov, 2010]. This confirms the reliability of the MSM results. Figure 2 shows that the boundaries of the Ust-Pinezhskaya formation were most distinct in the sedimentary cover, according to the Common Depth Point Method. These boundaries lose their contrast and experience distortions near the pipes of the Lomonosov deposit. Which confirms the development of faults in the strata above the Ust-Pinezhskaya Formation [Kalinin, 1989]. Several elementary faults are visible on the surface, which appear as near-surface contrast anomalies. It is likely that these manifestations of faults above the Vendian sediments are caused by the unloading of mineralized water [Stogniy and Korotkov, 2010].

In summary, the MSM data confidently revealed a controlling fault zone consisting of a series of elementary faults. These faults were observed as linear, vertical, narrow, and equidistant low-velocity contrast anomalies. They can be traced from depths of 100–200 m to 4 km or more. The fault zone has a meridional strike in terms of plan. Consequently, this structure appeared most confidently according to the data of sublatitudinal profiles. The elementary faults have most likely developed abrasion subzones, causing anomalous velocity lowering and a “super-resolution effect”. The pipes are directly associated with one of these faults. The controlling fault zone is most clearly manifested in the Ust-Pinezhskaya Formation of the Vendian sediments.

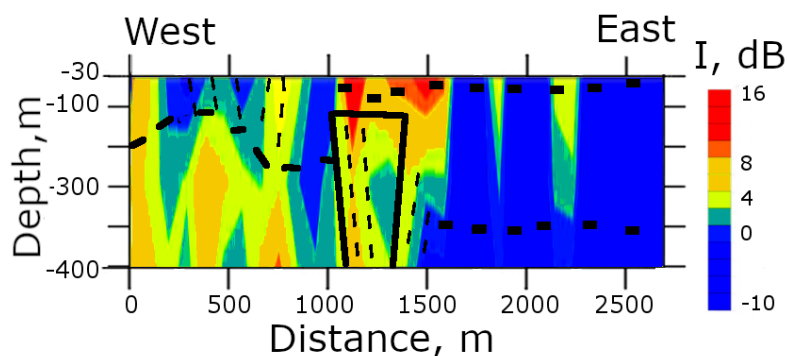


Figure 6. Results of the microseismic sounding method along a profile intersecting the Lomonosov pipe, with the overlay of boundaries identified based on the results of electrical prospecting [Stogniy and Korotkov, 2010].

5.2. Pipes Chidvinskaya, Verkhnetovskaya and C10

Figure 4 shows that the Chidvinskaya, Verkhnetovskaya and C10 pipes were identified as high-velocity anomalies, unlike the Lomonosov pipe. Additionally, a system of linear vertical faults similar to the controlling fault zone of the Lomonosov deposit was observed in the host medium of the Chidvinskaya and Verkhnetovskaya pipes. However, the contrast of these faults was significantly less than that of the faults of the Lomonosov deposit. The location of the profiles within the fault zone may explain the reduced contrast. Therefore, the average velocity is determined by the velocity of this fault zone.

Thus, the defining difference between the Chidvinskaya, Verkhnetovskaya, and Lomonosov pipes is their position relative to the edges of the controlling zones. The Lomonosov pipe is situated at the edge of the fault zone, while the Chidvinskaya and Verkhnetovskaya pipe are located within the fault zone. Figure 4 shows that the contrast between the pipe body and elementary faults is similar in all cases, ranging from 5–12 dB. The relative contrast between elementary faults and the medium is consistent at 3–6 dB for both cases. The width of elementary faults and the distance between them are also uniform, at 50 m and 200 m, respectively. Therefore, the Lomonosov, Verkhnetovskaya, and Chidvinskaya pipes are associated with fault zones of the first type, which have a similar structure and close relative contrasts.

Only one elementary fault, located at the edge of the profile at point 19 in the vicinity of the Chidvinskaya pipe, exhibits anomalous intensity values. This suggests that different elementary faults experienced different stresses during their formation and activation. A similar fault is located in close proximity to the Lomonosov pipe. To gain a more comprehensive understanding of the causes, it is important to conduct studies over a larger area in order to determine the boundaries of the fault zone and potential causes of the anomalous values.

The C10 pipe is situated in an inclined low-velocity zone, and its host medium differs significantly from the cases discussed above. No linear vertical abnormalities were detected. The contrast between the C10 pipe and its host medium is pronounced, measuring more than 20 dB, as well as with the fault. Additionally, high contrast is observed even between separate parts of the pipe. At the same time, the size of profiles and density of points outside the pipe is significantly lower than in studies of other pipes, which makes it difficult to compare the data.

6. Discussion

The upper boundary of the control zone of the Lomonosov deposit is delineated at various depths. Elementary faults do not extend above the Ust-Pinezhskaya Formation at a distance from the Lomonosov pipe. However, near the pipe, faults cross all Vendian sediments, with the most contrasting fault sections also located in the Ust-Pinezhskaya Formation. It can be assumed that the controlling structure was formed in the Ust-Pinezhskaya

Formation before the formation of the Mezenskaya Formation. The controlling structure formed during the Neoproterozoic period (650–610 Ma) [Stankovsky *et al.*, 1985], coinciding with the formation of the White Sea rift system [Baluev *et al.*, 2022]. During the Devonian–Carboniferous period, the fault system was activated, resulting in the uplift of kimberlite and the development of faults in the overlying Mezenskaya and Padunskaya formations of the Vendian.

Therefore, the formation of ore-controlling faults resulted from the development of previously formed faults. This is necessary for the explanation of the observed variations in control zone structure at different distances from the kimberlite pipe.

The elementary faults can be traced to different depths. It is interesting to note that the fault confined directly to the pipe has a minimum depth of 1.5 km. At the same time, the fault extending to depths of more than 4 km is located 1 km west of the pipe. However, it is clear that the kimberlite has been exhumed from greater depths. Furthermore, in paper [Danilov *et al.*, 2021] showed that the elementary fault controlling the Lomonosov pipe can only be traced to the north. It is reasonable to assume that the controlling faults have a complex geometry and are probably interconnected. This assumption is consistent with the results of independent studies of the Tolbachinsky volcano [Kugaenko *et al.*, 2018], where it was shown that the volcano has a complex system of vertical and horizontal supply channels. In this regard, it is important to continue studying the maximum trace depth of elementary faults at different distances from the pipes.

Figure 5 shows that diamondiferous pipes appear as low velocity inhomogeneities, while non-diamondiferous pipes appear as high velocity inhomogeneities.

Nevertheless, the velocity contrasts between the pipes and the elementary faults, as well as between the elementary fault and the medium between them, are quite close in all observed cases. Thus, the differences in the manifestation of the pipes on the MSM results are most likely related to the position of the pipes relative to the edges of the first type control zone. For example, the pipes of the Lomonosov deposit are located at the edge of the controlling fault zone [Stogniy and Korotkov, 2010]. Accordingly, about half of the profiles exit into the consolidated block of Vendian sediments, resulting in the pipes being characterised by reduced velocities compared to the undisturbed environment. Thus, the main difference between the studied diamondiferous and non-diamondiferous pipes is their position relative to the controlling fault zone. On the other hand, this may be due to the difficulty of detecting diamondiferous kimberlite pipes within fault zones. In particular, the probability of missing pipes using traditional methods is described in [Kutinov and Chistova, 2004].

According to seismic studies, the integral velocity reduction in fault zones of the first type is 5% [Kalinin, 1989]. At the same time, according to the MSM data, the velocity reduction in elementary faults is more than twice as high. At the same time, elementary faults extend throughout the depth of the sedimentary cover. The small contribution to the integral velocity characteristics of the fault zone can be explained by the fact that the fault zone has a small width. For example, there are 4 elementary faults in the 1200 m section. Accordingly, the average width of the fracture zone can be estimated to be 25 m. This estimate is consistent with the observed width of the elementary faults of 50 m. Thus, the observed velocity contrast, the density of elementary faults and their widths are consistent with the results of active seismic methods for estimating integral velocities. This agreement confirms the reliability of the observed data.

The structure of the host medium and the pipes is most contrasting in the sub-latitudinal profiles. This is most likely related to the fact that there are more contrasting changes in physical parameters when studies are conducted across controlling structures. In addition, sublatitudinal profiles cross the maximum number of elementary faults.

The exception to the observations made is the C10 pipe of the Nenoksa field. It belongs to a contrasting extensive fault zone, within which no elementary faults are identified. Perhaps the absence of pronounced elementary faults is a peculiarity of the Nenoksa field. In particular, it may be influenced by the fact that up to four phases of activation have been

identified in the Nenoksa field [Gubaidulin, 2001]. To answer this question, more detailed studies of different pipes of the Nenoksa field are required.

7. Conclusion

The first type of kimberlite-controlling fault zones were manifested in the MSM data as a series of vertical, narrow, linear elementary faults. A distinctive feature of the observed seismic pattern is the uniformity of the distribution of elementary faults, which can be traced from depths of 150 m through the entire sedimentary cover and into the crystalline basement. The average distance between elementary faults is 200–300 m, and their width is about 50 m. At the same time, the velocity of the shear wave decreases more than twofold in an elementary fault. Most likely, the velocity reduction occurs in the abrasion subzone. The pipes are connected to one of the elementary faults. Thus, elementary faults play a leading role in the formation of pipes. This fact emphasises the need for a more detailed study of such structures.

The controlling structures were probably originally formed in the Neoproterozoic. Activation in the Devonian-Carboniferous resulted in the formation of faults in the overlying Mezen and Padun formations in some areas. As a result, elementary faults can be traced through the entire thickness of the Vendian sediments in the vicinity of the pipes. At the same time, away from the pipes, the elementary faults do not extend above the Ust-Pinezhskaya Formation. Thus, the depth of the faults may be an indirect indication of the distance from the pipelines.

It is reasonable to assume that these faults must continue into the crystalline basement or be associated with other faults in the crystalline basement, which will require the implementation of larger scale studies.

The regularities revealed can be additional criteria for the selection of promising anomalies. During prospecting, it is advisable to identify structures with seismic patterns close to the established structure of the first-type fault zone, with subsequent tracing of elementary faults. The most effective controlling structures will be identified using data from sub-latitudinal MSM profiles. Particular attention should be paid to elementary faults on the sides of the control zone.

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