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Electrical Resistivity Dynamics Beneath the Weathered Mine Tailings in Response to Ambient Temperature

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ABSTRACT

Ore mining and processing dumps are open and technogenic systems, which change intensively with time under the influence of environmental factors. Active transformations of such "technogenic deposits" are in close relationship with environmental factors. The purpose of this paper is to determine the nature and causes of the electrical resistivity (ER) changes in the mine tailings dump over time. The investigations were carried out by the method of electrotomography by determining the ER of the section to a depth of 1.5 m with an interval of one hour during the day with simultaneous recording of the substance temperature at a depth of 0.1 m. The maximum daily ER dynamics is observed over intensely transformed technogenic ores. ER is in a numerical relationship with the temperature of the solid matter by an exponential law with a certainty of 96%. A direct dependence of the ER daily changes amplitude on the cementation index m was revealed with the help of the Archie law. The primary material of the heap has a monodisperse composition and small values of m, so the amplitude of the ER dynamics is minimal. As a result of oxidative transformations, the solid matter of the dump becomes polydisperse, which is reflected in the cementation index and the amplitude of the ER daily oscillations increase.

INTRODUCTION

Mineral raw materials are subjected to crushing and no-equilibrium intensive dispersion in the process of extraction and processing. As a result, finely ground sulfide-containing wastes are formed. These mine tailings have a large specific surface area and a high reactivity (Blowes *et al.*, 2003). Oxidation of sulfide minerals by air and oxygen leads to the formation of acid drainage with high concentrations of sulfate anions, ore metals (Fe, Ci, Zn, Cd, Pb) and impurities (As, Sb, Be, Se) (Dold, 2014; Nordstrom *et al.*, 2015; Parbhakar-Fox and Lottermoser, 2017). Oxidative transformations of mine tailings are characterized by higher rates of weathering (Ptitsyn, 2006; Lindsay *et al.*, 2015; Abrosimova *et al.*, 2015) and increased migration of chemical elements (Vernadsky, 2002; Fersman, 1955; Lukashev, 1986). The numerous negative consequences of sulfide-containing tailings oxidizing due to the acid, metals and metalloids removal with drainage waters (Kossof *et al.*, 2014; Nordstrom *et al.*, 2015; Cidu *et al.*, 2017; Korneeva *et al.*, 2017), soil, snow cover and the atmosphere pollution (Banic *et al.*, 2006; Yurkevich *et al.*, 2015; Noble *et al.*, 2017; Benyassine *et al.*, 2017, Bortnikova *et al.*, 2017, 2018) are described. In addition, the perspectives for valuable components extracting from wastes exist. Often high concentrations of Cu, Zn, Ag, Au make such processing economically profitable and allow us to recover tailings (Ptitsyn, 2006; Yurkevich *et al.*, 2017).

One of the main factors of oxidative transformation in mine tailings are temperature fluctuations, under the influence of which the electrochemical reactions at the boundary of ore minerals and pore water become activated or disappear (Sveshnikov, 1967; Ptitsyn, 2006), chemical and physical destruction of matter occurs (Shesternev, 2001; Tataurov, 2008). For example, mineralization zones have rapidly changing physical properties that lead to the dynamics of local geophysical fields (Balasanyan, 1990). The effect of the geoelectric field daily dynamics was discovered in the middle of the last century. It consists in the daily electrical resistivity (ER), the natural field potential and the induced polarization variations, when the external and, consequently, internal properties of the medium change (Semenov, 1957; Balasanyan, 1990). Time-varying behavior of geoelectric fields is most often observed in ore deposits and fault zones (Avgulevich, 2003). In addition, there are many studies on the dynamics of resistance during the penetration of a substance into the medium (tracer tests) or during seasonal changes on different sites (Hauck, 2002; Hayley *et al.*, 2007; Oldenborger *et al.*, 2007;

Chambers *et al.*, 2014; Lin *et al.*, 2018; Chen *et al.*, 2019).

First investigations of mining dumps using geophysical methods were conducted about 20 years ago (Yuval and Oldenburg, 1996). The use of electrical prospecting methods allow to reduce significantly the number of sampling points for geochemical research, to estimate the volume and resources of "man-made deposits" and to outline the pore fluid distribution zones (Campbell, 1999; Buselli and Lu, 2001; Horton, 2003; Rucker, 2009, Burton and Ball, 2010; Placencia-Gómez, 2010; Parasnis, 2013; Khalatov *et al.*, 2013; Yurkevich *et al.*, 2017). A common practice is the construction of geoelectrical sections and their interpretation at a qualitative level with the prediction of the conducting zones confined to horizons of highly mineralized pore solutions (Bortnikova *et al.*, 2013; Acosta *et al.*, 2014; Olenchenko *et al.*, 2016; Martínez-Pagán *et al.*, 2009, Martín-Crespo *et al.*, 2018).

However, the studies known to date do not touch upon the temporal changes in the physical properties of the tailings, which occur during oxidative transformation. However, the resistivity is a complex electrical characteristic of the soil, influenced by various parameters: particle size, permeability, temperature, porosity, tortuosity, pressure, and clay content (Friedman, 2005) all of which may vary with time. The temperature and the structure of the substance play a central role among these factors.

The aim of this study is to determine the relationship between the resistivity, the temperature and the structure of mine tailings in the oxidative zones. The main objective of our investigations is to reveal the nature and causes of the daily changes in the electrophysical parameters of the mine tailings.

Our investigations aim to determine the water and air dispersion ways of elements out from sulfide-bearing mine tailings, depending on the composition of the tailings, as well as changes in external environmental parameters: temperature, humidity, pressure, the Earth's electric field. The practical application of this work is a prediction the periods of the greatest toxicity of a mine waste (during the day and the year). This is especially actual in a region with a sharply continental climate, like Siberia, when seasonal variations in environmental conditions lead to significant changes in the ground. Moreover, as we have already indicated, changes in mine tailings are even more pronounced than for natural soils: the finely crushed tailings with a large area of reactively active surface transform (including oxidize) intensively due to seasonal freezing and thawing of water in cracks.

In addition, the observation of the diurnal and seasonal dynamics of electrophysical parameters and their relationship with the waste's composition and structure forms the basis for the geophysical monitoring of waste processing and territory remediation.

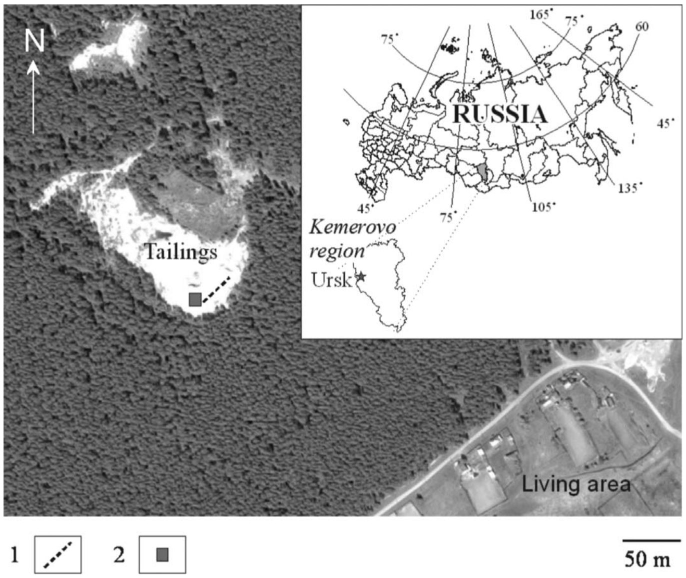

Figure 1 The location of the Beloklyuchevsky tailing, the profile of electrotomography and thermometric measurements (1), and soil pit (2).

STUDY AREA

The Beloklyuchevsky mine tailings are located in Ursk village, Kemerovo region, at a distance of 300 m from the living area: 54.463326 0N, 85.386502 0E (Fig. 1). The tailings were accumulated after the processing of ores from the Beloklyuch deposit, which is the part of the Ursk's ore field. The tailing dump was created in the 1930s and was used until the 1970s. The structure, morphology, mineral composition of ore bodies, the sequence of mineral formation, the mine development have been studied and described by many researchers (Bolgov, 1937; Zerkalov, 1959; Distanov, 1977). Ore bodies of the deposit are represented by massive sulfur-pyrite and pyrite-polymetallic ores, vein-disseminated and disseminated by pyrite-copper-zinc ores, hemmed-in by a halo of disseminated mineralization. The shape of the ore bodies is lenticular; the main vein minerals are quartz, sericite, barite, calcite, gypsum. The main sulfide components of the ores are pyrite, arsenopyrite, sphalerite, chalcopyrite, fahlite, and galena. Rare minerals: pyrrhotite , argentite, gold, altaite, hessite, calaverite, stibnite, clausthalite (Zerkalov, 1959). The upper parts of the ore bodies (quartz-barite and quartz-pyrite fain-grained sand) from which gold was extracted by cyanidation.

The tailing in the section is an alternation of color contrasting layers: from bright red to greenish and bluish gray, depending on the degree of matter oxidation. Modern geochemical composition of the

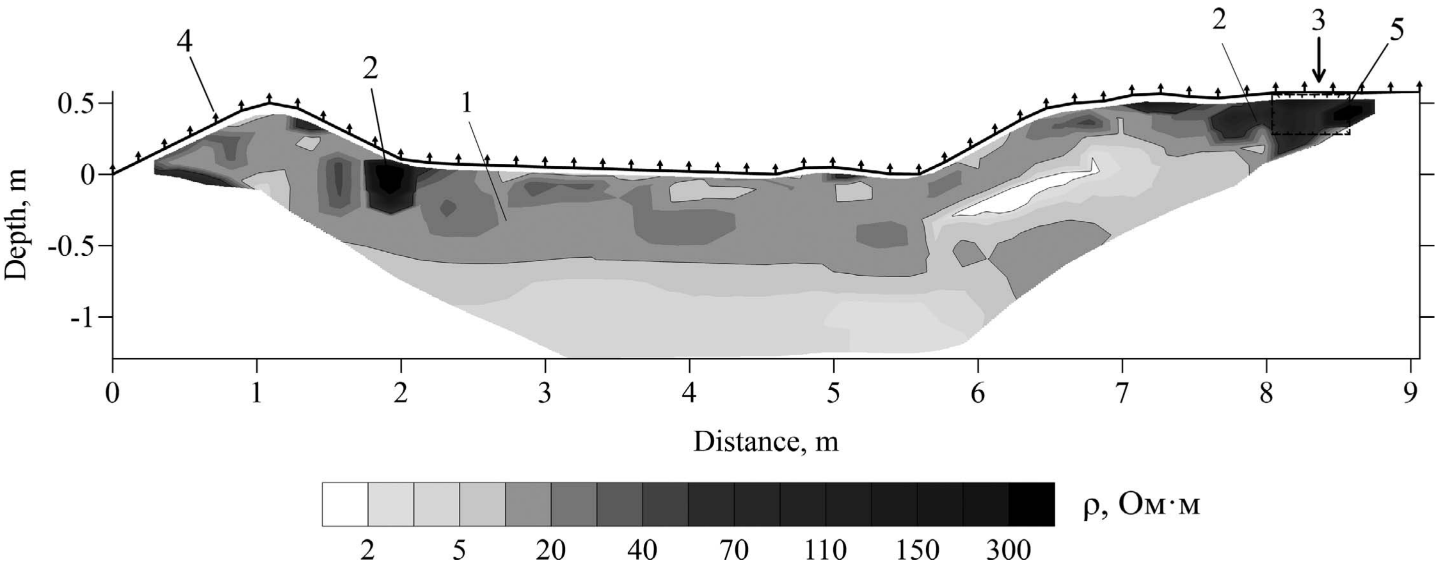

Figure 2 Geoelectrical section at 16:00: 1 – primary tails, 2 – oxidized tails, 3 – temperature sensor, 4 – electrodes, 5 – pit.

tailing is determined by two main factors: primary heterogeneity of the stored material and secondary processes of its redistribution.

METHODS

Geophysical Investigations

Electrical resistivity tomography was used to investigate the mine tailings. The measurements were performed using a multielectrode instrument SKALA-48. A dipole-dipole array was use as the sequence of connecting the electrodes. The number of electrodes was 48. The interelectrode distance was 0.2 m. The length of the profile was 9.4 m. The depth of the investigation was up to 1.5 m. Thus, factor values $a = 0.2$, $n = 1$. The maximum signal error was 0.9%. The resistivity values were measured every hour during the day from 16:00 on July 1, 2017 until 15:00 on July 2, 2017. The measurement array was 526 points for each hour of measurement. Data processing was performed using the program of two-dimensional inversion Res2Dinv (Loke, 2010). The robust smoothness constrain method was used.

Study of the Temperature and Composition of the Solid Matter

The temperature of the tailings was determined at a depth of 0.1 m at the point of 8.3 m of the profile by a laboratory electronic thermometer LT-300 (–50 ... +300°C) with a stainless steel sensor. Samples of solid matter were taken from one test-pit of 1 m deep in visually different horizons at the point of 8–8.5 m of the profile (Fig. 2) which correspond to the zone with maximum of electrical resistivity (red-orange tails). Solid samples were divided into two sets. The granulometric composition of the solid matter was determined from the first set using sieve on a fraction >704 μm and the particle size analyzer Microtrac X100 for the particles in the range from 0.04 to 704 μm. The second set of the solid samples was dried at room temperature for 48 hours, homogenized by folding, and powdered to <74 μm by abrasion in an agate mortar for laboratory experiments.

Laboratory Experiments on the Relationships between Resistivity and Temperature of the Pore Fluid

Three laboratory experiments were performed to reveal the relationship between resistivity and ambient temperature for the: 1) NaCl solution (the model of the mineralized pore solution); 2) pore fluids; and 3) pastes (model of the wet solid skeleton). The first experiment was carried out with a NaCl solution (5 g/L). It was cooled to +5°C, and then heated using digital magnetic stirrer WiseStir MSH-20D-Set (DAIHAN Scientific) to +100°C. The conductivity value was measured at each 5°C step using portative device Cond-315i (WTW, Germany) and the resistivity value was calculated.

For the second experiment, the sample of the waste was cone quartered and dried at room temperature to constant weight. The sample was used to extract aqueous leaching solutions by the scheme: 20 g of the sample was left in 400 ml of double-distilled water for 24 h on a magnetic stirrer. Aliquot of the obtained solution was separated from solid by filtering of the aqueous extract through a 0.45 μm membrane filter. Measurements of the resistivity were carried out in the same way as for the first experiment.

For the third experiment, the sample of the waste was cone quartered and dried at room temperature to constant weight. 100 ml of double-distilled water was

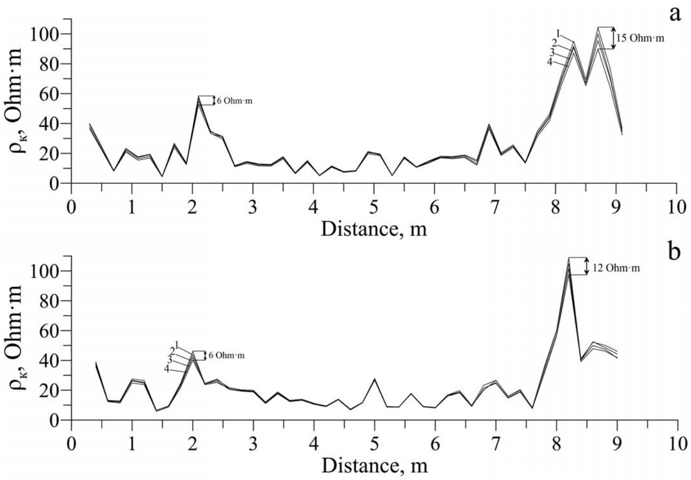

Figure 3 Graphs of the resistivity: a) pseudodepth 0.08 m (1 - 7:00, 2 - 02:00 , 3 - 12:00, 4 - 15:00); and b) pseudodepth 0.14 m (1 - 8:00; 2 - 23:00, 3 - 12:00, 4 - 16:00).

added to 50 g of the sample to prepare paste, which simulate the moistened tailings, the paste was left for 24 h on a magnetic stirrer. The cooling to +5°C and heating to +100°C with measuring of the resistivity were carried out in the same way as described for the experiment 1.

Calculation of Relationship between Resistivity and Cementation Index

The relationship between the resistivity of the pore solution and the resistivity of the whole substance is described by Archie's law (Archie, 1942):

$$\frac{\rho}{\rho_w} = \phi^{-m}, \tag{1}$$

where ρ is the resistivity of the rock, ohm·m, ρ_w is the specific resistivity of the pore solution, ohm·m, φ is the porosity coefficient, m is the cementation index responsible for the pore size distribution with respect to the average pore size, or for the dispersion (Friedman, 2005; Murcovkin, 2014). Then, according to the Eq. (1), the resistivity of the substance (ρ) was calculated using the resistivity of the pore solution obtained in the laboratory (ρ_w from second experiment) and the parameter $\varphi = 0.4$. Using different values of the cementation index m from 1.4 to 2.6 with increment 0.4, we calculated the models of the time scales of the resistivity (Friedman, 2005; Zhang *et al.*, 2012).

RESULTS AND DISCUSSION

Geoelectrical Sections

The resistivity values of the materials vary from 0.3 to 300 ohm·m (Fig. 2) at the starting time (16:00). A wide range of resistivity is associated with different material composition and acidity of the pore fluid. To a depth of 0.5 m the rocks have an increased resistivity of 10–50 ohm·m with inclusions of local sections with anomalously high to 100–300 ohm·m and low to 1 ohm·m resistivity. This is the most heterogeneous part of the geoelectrical section. The resistivity of the substance varies little—within 3–5 ohm below the depth of 0.5 m that indicates a homogeneous material composition of the tailings. Substance with a resistivity of 10–20 ohm·m correlated with not modify gray-blue tailings. Near-surface zones of high resistivity these are intensely oxidized tailings of red-orange color. The anomaly with a resistivity of less than 2 ohm·m is associated with rocks with a high acidity of the pore fluid.

Variability of Resistivities Along the Profile

Areas with maximum changes in resistivity at the site can be detected by using function of the time-lapse inversion in a two-dimensional inversion program. However, such an approach can lead to artifacts in sections showing relative changes in resistivity. In order to reduce such artifacts, the Res2Dinv program uses a simple damped or Marquardt constraint, L2 least squares smoothness and L1 norm constraint or robust (Loke, 2001). At the same time, the paper of (Modin *et al.*, 2014) showed that even in the presence of relatively small interference (within 3%), a formal two-dimensional inversion will produce different results depending on the structure of the interference field with an increase in this negative trend as the separation increases. Therefore, in order to avoid the ambiguity of the interpretation associated with the inversion instability, we will consider the change in apparent resistivity in time.

The graphs of the resistivity were constructed to analyze the changes in the electrical properties of matter during the day along the profile (Fig. 3). We have taken the data obtained at 0.2 m and 0.3 m offsets assuming that the maximum changes will occur at shallow depths. They correspond to pseudo depths of 0.08 m (Fig. 3(a)) and 0.14 m (Fig. 3(b)). In some parts of the profile (0–3 m and 8–9 m), the apparent resistivity values varied significantly during the day. In other intervals (3–6 m), the value of resistivity during the day almost did not change.

For determining the points with the most intensive resistivity's change, the graphs of the maximum daily dynamics were plotted (Fig. 4), which is calculated by the formula $\delta_{\rho k} = \rho_{max}$-$\rho_{min}$. The background value (median of the series) $\delta_{\rho k}$ is equal to 1.92 ohm·m. At a distance of 2 m and 8–9 m from the beginning of the profile, the values of the resistivity's dynamics are increased (more than 2 ohm·m). The maximum value of $\delta_{\rho k}$, reaching 15

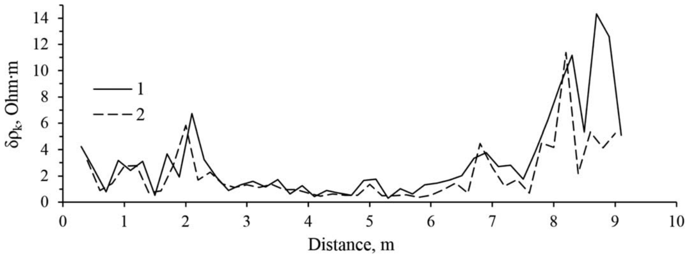

Figure 4 The graph of the maximum daily resistivity's dynamics along the observation profile, with curve 1 representing pseudodepth 0.08 m and curve 2 representing pseudodepth 0.14 m.

ohm·m, is observed at a distance of 8.7 m from the beginning of the profile at a depth of 0.14 m. An analysis of the data showed that the intense dynamics of ρ_k is manifested in the zones of anomalies of high resistivity (Fig. 2), which are associated with a strongly modified solid matter.

Variability of Resistivities During the Time of Observation

The resistivity values should be brought to the same scale for determining the resistivity variations with time at each electrode position. For this purpose, the measured value at each time was reduce by the mean value at the electrode position during the observation period according to the formula $\Delta\rho_k$ (t) $= \rho_k$ (t) – ρ_k^{mean}. The change of this quantity in time is called the time series.

Further analysis examines in detail the data that correspond to the positions of the electrodes at intervals with a maximum daily dynamics (2–2.5 m, 8–9 m). Figure 5(a) shows the time series for each electrode position at pseudodepth of 0.08 m. Time series for the positions 2.1 m, 7.9 m, 8.1 m, 8.3 m, 8.7 m and 8.9 m (intervals of maximum dynamics) at pseudo-depths are signed. Also shown in Fig. 5(b) are time series for a pseudo-depth of 0.14 m. We note that time series that have a high amplitude are those that are located in intervals with maximum dynamics. Specific resistivity time series have common-mode changes with a maximum of 7:00–8:00 hours and a minimum of 15:00 for different positions of the profile electrode at the same depth. This suggests that the change in resistivity across the profile is caused by an external influence of the same nature. The maximum resistivity time is shifted by one hour to 8:00–9:00 at a depth of 0.14 m, but their changes are also in phase.

When comparing time series of apparent electrical resistivity with a graph of temperature change (T) at a depth of 0.1 (Fig. 5(c)), the interrelation between these variables is obvious. The amplitude $\Delta\rho_k$ increases with temperature decreasing, an inverse relationship of the resistivity with the temperature is observed. Thus, the external physical factor, affecting the resistivity of the tailings during the day, is the air temperature, which determines the temperature of tailings. The relationship of the apparent resistivity at a pseudo depth of 0.08 m and the temperature of the substance at a depth of 0.1 m is described by an exponential law (Fig. 6). The correlation coefficient is –0.94. The exponential relationship between the soil's resistivity and its temperature is described in (Besson, 2008; Ma, 2011).

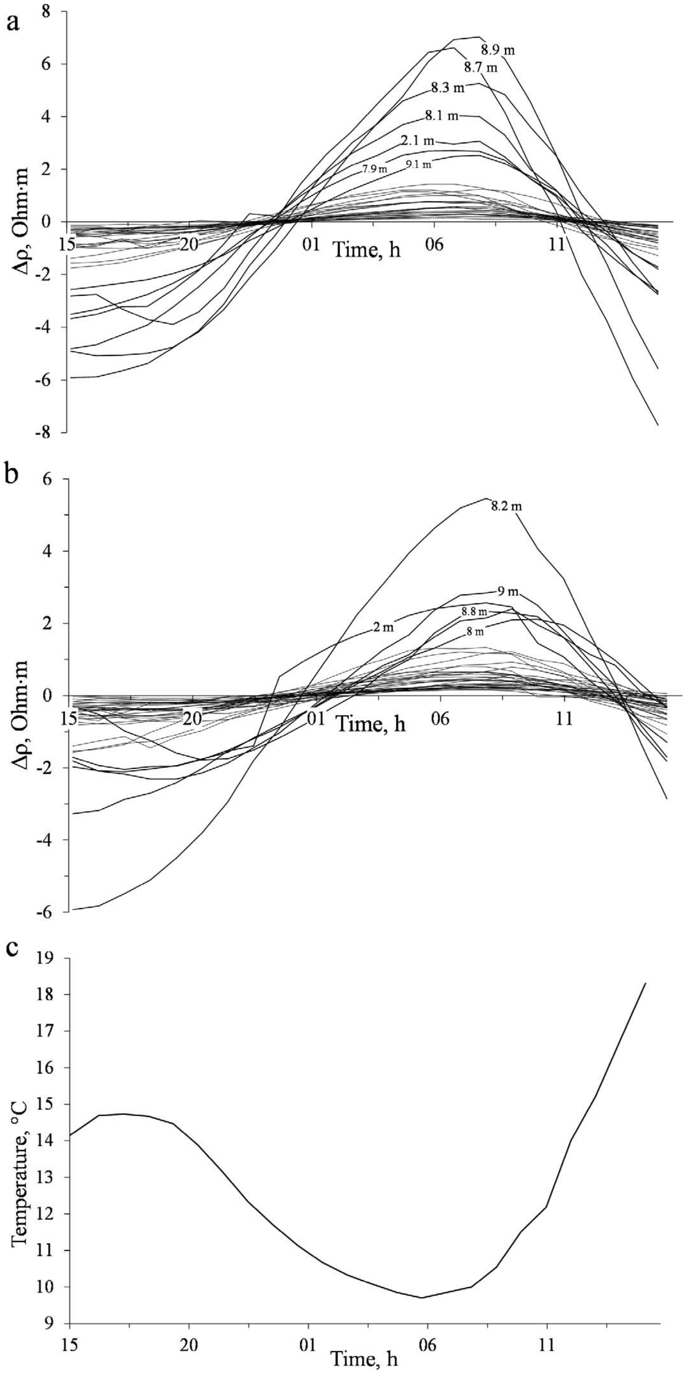

Figure 5 Comparison of changes in resistivity and temperature over: a) Time series for each electrode position at pseudodepth of 0.08 m; b) time series for each electrode position at pseudodepth of 0.14 m; and c) daily variation of temperature.

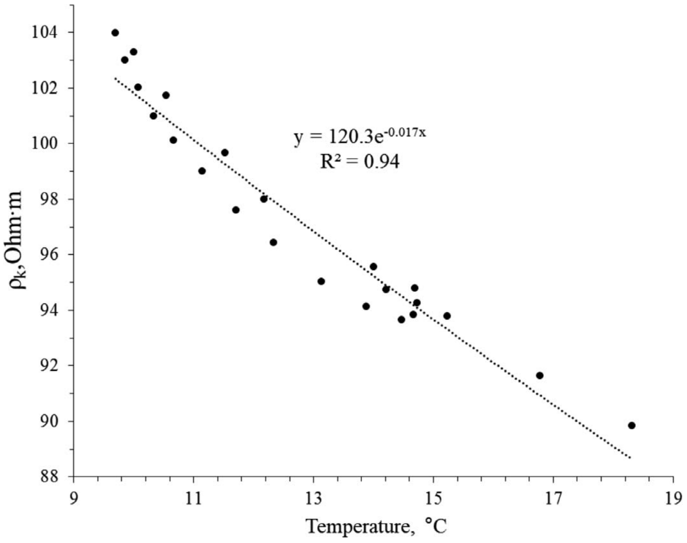

Figure 6 The dependence of the tailings resistivity on its temperature on pseudodepth 0.08 m.

The Dependence of Resistivities of NaCl Solutions and Pore Fluids from Temperature

Electrical resistivity is a complex electrical characteristic of the soil, which is affected by various parameters of the substance. However, for rocks with a non-conductive skeleton, the conductivity of the pore solution and the water content are the dominant factors affecting the conductivity of the whole substance. At the Beloklyuchevsky mine tailings the conductivity of waste is not due to humidity, but is directly related to its chemical composition. In this case, the temperature of the substance plays a central role among the factors that determine the resistivity of the substance. A change in ambient temperature leads to a change in the temperature of the pore fluid. To identify the relationship between the resistivity of the substance of the blade and the temperature, three laboratory experiments were performed: with NaCl solution (model of mineralized pore solution), with water extract from the substance (pore fluid), with paste (model of a wet solid skeleton).

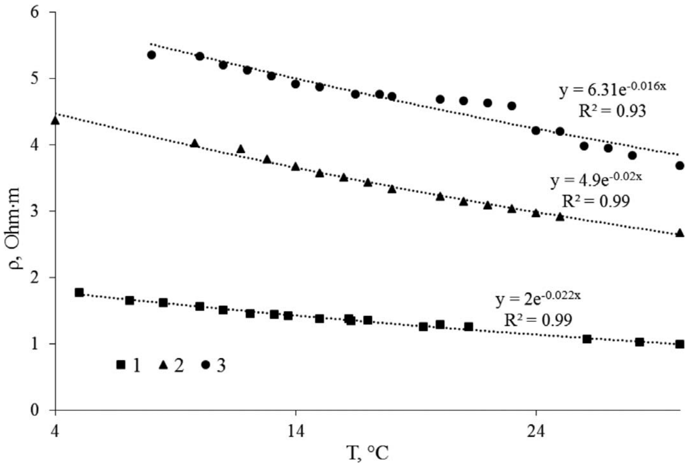

Figure 7 Dependences of resistivity on temperature from the results of a laboratory experiments with curve 1 representing NaCl, curve 2 representing extract, and curve 3 representing paste.

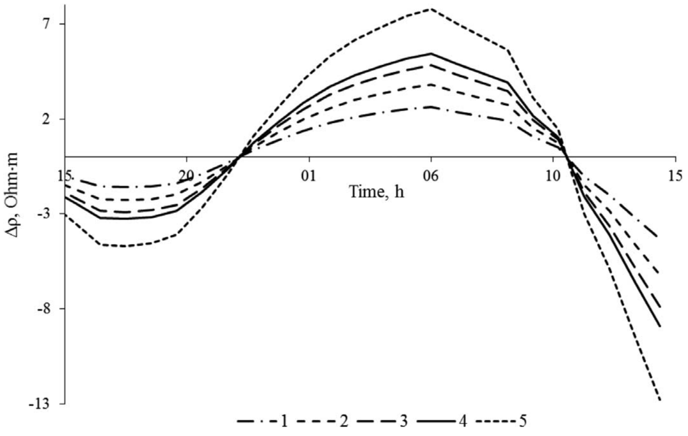

Figure 8 Temporal development of the normalized values of the resistivity for the resistivity of the rock, calculated according to Archie's law, for different m: 1 – m = 1.2, 2 – m = 1.5, 3 – m = 1.7, 4 – m = 1.8, 5 – m = 2.

As a result of the experiment, the exponential dependences of the resistivity of NaCl solution, aqueous extract and paste from the dump material and temperature were determined. Figure 7 shows the dependences of the resistivity of NaCl solution, aqueous extract and paste from the dump material, and temperature. Charts vary exponentially. The same dependences for the models of the pore solution and the solid moistened substance suggest that the resistivity of a solid in this case depends to the maximum extent on the conductivity of the pore solution.

The Relationship between Resistivity and Cementation Index

Figure 8 shows the models of the resistivity time scans for different parameters of the cementation index *m*. The maximum amplitude of the daily dynamics of resistivity is observed in the substance having the largest index *m*, that is, high dispersity. The results obtained are consistent with Friedman's (2005) and Murtsovkin's studies (2013), which indicate that the greater the dispersion of grain sizes relative to the average size, the higher the resistivity of the medium for the same porosity.

Consider the particle size distribution in the material samples from the tailing (Fig. 9). The fractions of grains of different diameters are determined for primary and oxidized substances from the surface (a) and from a depth of 0.15 m (b). Primary (non-oxidized) tailings from the surface are mainly particles of about 0.83 μm in size. Oxidized ores have a polydisperse composition and contain particles rang-

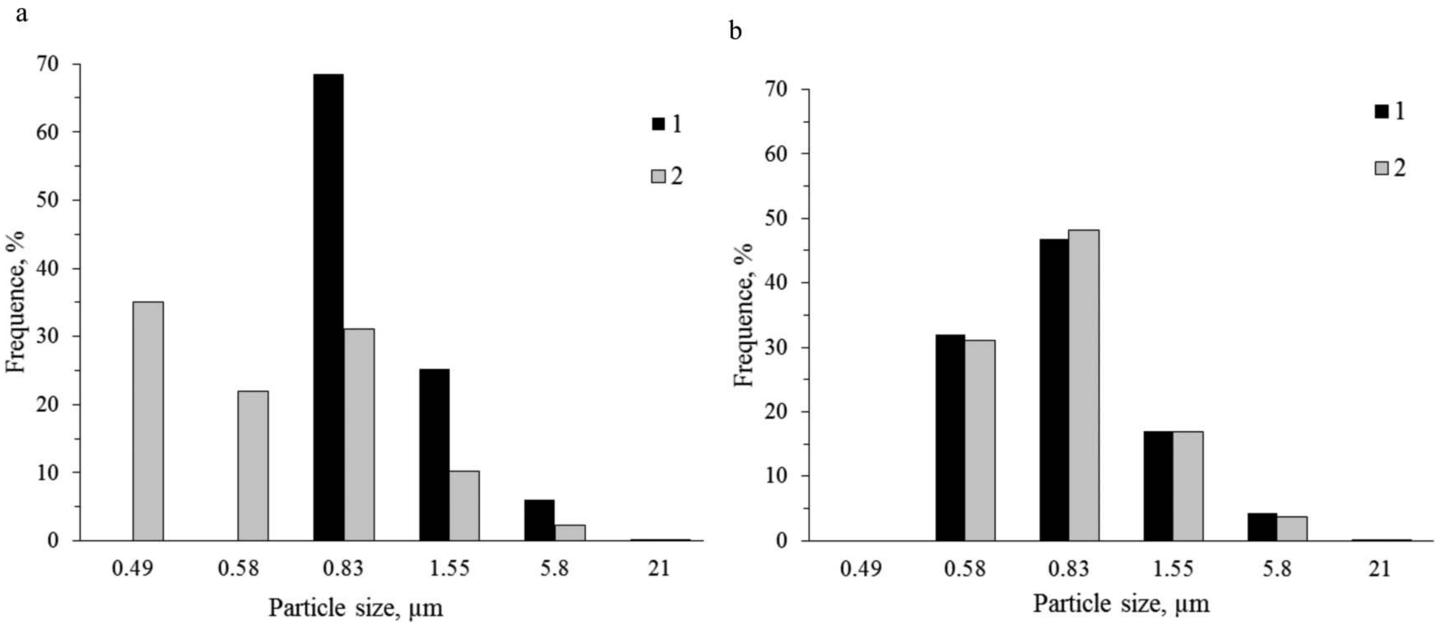

Figure 9 Size distribution histograms for the mine tailings particles in: a) On the surface; and b) at a depth of 0.15 m; 1 – unoxidized substance, 2 – oxidized substance.

ing in size from 0.49 to 1.55 μm. An equal number of particles of different diameters are present on a depth of 0.15 m in the primary and oxidized sites.

The maximum dynamics of resistivity is manifested in zones of high resistivity corresponding to oxidized ores. As a result of oxidation, these ores acquire a polydisperse composition in the near-surface part of the section. In addition, the greater the spread of grains relative to the average size, the higher the amplitude of the resistivity.

RESULTS AND DISCUSSION

In the course of the study, the daily dynamics of the electrical resistivity of the material in a sulfide-containing tailings deposit were studied in order to identify patterns and causes. As a result, the following was established.

1. Using electrotomography data, the presence of diurnal variations of the electrical resistance in the upper part of the section has been established. The maximum changes are confined to the zones of increased resistivity associated, which are with intensely oxidized substances, subject to intense oxidative transformations.
2. The inverse relationship of time-varying electrical resistivity with the material temperature is shown. This suggests that temperature is a determining factor in the nature of the dynamics of resistivity.
3. Using different cementation index in Archie's law, showed that the amplitude of the resistivity dynamics depends on the cementation index, which in turn is determined by the polydispersity of the composition. An increase in the amplitude of resistance dynamics with an increase in the heterogeneity of the composition of the substance was found.

Due to this study, it was determined that the oxidized substance is most susceptible to changes in resistance due to temperature fluctuations. This substance contains more sulphides. This is also confirmed in other works, where the dynamics was detected over ore deposits containing sulphide minerals (Semenov, 1957; Balasanyan, 1990; Avgulevich, 2003).

References

Abrosimova, N., Bortnikova, S., Gaskova, O., Yurkevich, N., and Ribkina, E., 2015, Results of mine tailings-water interaction: A column leaching study on the example of waste materials of Komsomolsky gold processing plant, *in* 15th International Multidisciplinary Scientific GeoConference SGEM 2015, Surveying Geology and Mining Ecology Management, pp765–770.

Acosta, J.A., Martínez-Pagán, P., Martínez-Martínez, S., Faz, A., Zornoza, R., and Carmona, D.M., 2014, Assessment of environmental risk of reclaimed mining ponds using geophysics and geochemical techniques: Journal of Geochemical Exploration, **147**, 80–90.

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Transactions of the AIME, **146**, 54–62.

Avgulevich, D.L., 2003, Investigation of the time-varying natural electric fields of the Earth in order to identify patterns of their formation and improve the method of the natural electric field: Doctoral dissertation. (in Russian)

Balasanyan, S., 1990, Dynamic geoelectric: Syu Balasanyan, Novosibirsk, Science.

Banic, C., Leaitch, W.R., Strawbridge, K., Tanabe, R., Wong, H., Gariépy, C., and Skeaff, J., 2006, The physical and chemical evolution of aerosols in smelter and power plant plumes: an airborne study: Geochemistry: Exploration, Environment, Analysis, **6**, 111–120.

Benyassine, E.M., Lachhab, A., Dekayir, A., Parisot, J.C., and Rouai, M., 2017, An application of electrical resistivity tomography to investigate heavy metals pathways: Journal of Environmental and Engineering Geophysics, **22**, 315–324.

Besson, A., Cousin, I., Dorigny, A., Dabas, M., and King, D., 2008, The temperature correction for the electrical resistivity measurements in undisturbed soil samples: Analysis of the existing conversion models and proposal of a new model: Soil Science, **173**, 707–720.

Blowes, D.W., Ptacek, C.J., Jambor, J.L., and Weisener, C.G., 2003, The geochemistry of acid mine drainage: Treatise on Geochemistry, **9**, 612.

Bolgov, G.P., 1937, Sulfides of Salair: Urskaya group of polymetallic deposits: Tomsk Industrial Institute, Tomsk, Russia. (in Russian)

Bortnikova, S.B., Olenchenko, V.V., Gaskova, O.L., Chernii, K.I., Devyatova, A.Y., and Kucher, D.O., 2017, Evidence of trace element emission during the combustion of sulfide-bearing metallurgical slags: Applied Geochemistry, **78**, 105–115.

Bortnikova, S.B., Yurkevich, N.V., Abrosimova, N.A., Devyatova, A.Y., Edelev, A.V., Makas, A.L., and Troshkov, M.L., 2018, Assessment of emissions of trace elements and sulfur gases from sulfide tailings: Journal of Geochemical Exploration, **186**, 256–269.

Bortnikova, S., Yurkevich, N., Bessonova, E., Karin, Y., and Saeva, O., 2013, The combination of geoelectrical measurements and hydro-geochemical studies for the evaluation of groundwater pollution in mining tailings areas: Threats to the Quality of Groundwater Resources, Springer, Berlin, Heidelberg.

Burton, B.L., and Ball, L.B., 2011, Geophysical investigation of Red Devil mine using direct-current resistivity and electromagnetic induction, Red Devil, Alaska: US Geological Survey, pp2011–1035.

Buselli, G. and Lu, K., 2001, Groundwater contamination monitoring with multichannel electrical and electromagnetic methods: Journal of Applied Geophysics, **48**, 11–23.

Campbell, D.L., Horton, R.J., Bisdorf, R.J., Fey, D.L., Powers, M.H., Fitterman D.L., 1999, Some geophysical methods for tailings/mine waste rock, *in* Proc. Sixth Int. Conf. Tailings and Mine Waste, Fort Collins, CO.

Cidu, R., Dore, E., Biddau, R., and Nordstrom, D.K., 2017, Fate of Antimony and Arsenic in contaminated waters at the abandoned Su Suergiu mine (Sardinia, Italy): Mine Water and the Environment, 1–15.

Chambers, J.E., Gunn, D.A., Wilkinson, P.B., Meldrum, P.I., Haslam, E., Holyoake, S., and Wragg, J., 2014, 4D electrical resistivity tomography monitoring of soil moisture dynamics in an operational railway embankment: Near Surface Geophysics, **12**, 61–72.

Chen, B., Garré, S., Liu, H., Yan, C., Liu, E., Gong, D., and Mei, X., 2019, Two-dimensional monitoring of soil water content in fields with plastic mulching using electrical resistivity tomography: Computers and Electronics in Agriculture, **159**, 84–91.

Distanov, E.G., 1977, Pyrite-polymetallic deposits of Siberia, Novosibirsk: Nauka. (in Russian)

Dold, B., 2014, Evolution of acid mine drainage formation in sulphidic mine tailings: Minerals, **4**, 621–641.

Epov, M.I., Yurkevich, N.V., Bortnikova, S.B., Karin, Y.G., and Saeva, O.P., 2017, Analysis of mine waste by geochemical and geophysical methods: A case study of the mine tailing dump of the Salair ore-processing plant: Russian Geology and Geophysics, **58**, 1543–1552.

Fersman, A.E., 1955, Selected works. Vol. 3: Publishing House of the Academy of Science of the USSR, Moscow.

Friedman, S.P., 2005, Soil properties influencing apparent electrical conductivity: A review: Computers and Electronics in Agriculture, **46**, 45–70.

Hayley, K., Bentley, L.R., Gharibi, M., and Nightingale, M., 2007, Low temperature dependence of electrical resistivity: Implications for near surface geophysical monitoring: Geophysical Research Letters, **34**.

Hauck, C., 2002, Frozen ground monitoring using DC resistivity tomography: Geophysical Research Letters, **29**, 12–1.

Horton, R.J., 2003, Electrical property measurements of mine waste from the Sunday #2 and Venir mines: Open-File Report 03-149, US Geological Survey, Leadville, Colorado.

Khalatov, S., Balkov, E., Bortnikova, S., Saeva, O., and Korneeva, T., 2013, Geoelectric methods of exploration for dumps of ore industry, *in* Geophysics 2013 – 9th EAGE International Scientific and Practical Conference and Exhibition on Engineering and Mining Geophysics.

Korneeva, T.V., and Aminov, P.G., 2011, Geochemistry of interaction of mine drainage of Mednogorsk geotechnical system with rivers as a natural hydrochemical barriers, *in* 15th International Water Technology Conference, IWTC.

Lin, C.H., Lin, C.P., Hung, Y.C., Chung, C.C., Wu, P.L., and Liu, H.C., 2018, Application of geophysical methods in a dam project: Life cycle perspective and Taiwan experience: Journal of Applied Geophysics, **158**, 82–92.

Lindsay, M.B., Moncur, M.C., Bain, J.G., Jambor, J.L., Ptacek, C.J., and Blowes, D.W., 2015, Geochemical and mineralogical aspects of sulfide mine tailings: Applied Geochemistry, **57**, 157–177.

Loke, M.H., 2001, Constrained time-lapse resistivity imaging inversion, *in* Symposium on the Application of Geophysics to Engineering and Environmental Problems.

Loke, M.H., 2010, Tutorial: 2-D and 3-D electrical imaging surveys, pp1–145.

Lukashev, V.K., 1986, Some scientific and applied problems of supergene geochemistry in the USSR. Applied Geochemistry, **1**, 441–449.

Martín-Crespo, T., Gómez-Ortiz, D., Martín-Velázquez, S., Martínez-Pagán, P., De Ignacio, C., Lillo, J., and Faz, Á., 2018, Geoenvironmental characterization of unstable abandoned mine tailings combining geophysical and geochemical methods (Cartagena-La Union district, Spain): Engineering Geology, **232**, 135–146.

Ma, R., McBratney, A., Whelan, B., Minasny, B., and Short, M., 2011, Comparing temperature correction models for soil electrical conductivity measurement: Precision Agriculture, **12,** 55–66.

Martínez-Pagán, P., Cano, Á.F., Aracil, E., and Arocena, J.M., 2009, Electrical resistivity imaging revealed the spatial properties of mine tailing ponds in the Sierra Minera of Southeast Spain: Journal of Environmental and Engineering Geophysics, **14**, 63–76.

Modin, I.N., Makarov, D.V., and Aleksandrov, P.N., 2014, Possibilities of electro-tomographic stations when performing monitoring observations: Engineering surveys, **9-10**, 22–31. (in Russian)

Murtsovkin, V.A., 2013, Electrical conductivity of porous media with two-phase saturation: Colloid Journal, **75**, 103–111.

Noble, T.L., Parbhakar-Fox, A., Berry, R.F., and Lottermoser, B., 2017, Mineral dust emissions at metalliferous mine sites: Environmental Indicators in Metal Mining, Springer, Cham.

Nordstrom, D.K., Blowes, D.W., and Ptacek C.J., 2015, Hydrogeochemistry and microbiology of mine drainage: An update: Applied Geochemistry, **57**, 3–16

Oldenborger, G.A., Knoll, M.D., Routh, P.S., and LaBrecque, D.J., 2007, Time-lapse ERT monitoring of an injection/withdrawal experiment in a shallow unconfined aquifer: Geophysics, **72**, F177–F187.

Olenchenko, V.V., Kucher, D.O., Bortnikova, S.B., Gas'kova, O.L., Edelev, A.V., and Gora, M.P., 2016, Vertical and lateral spreading of highly mineralized acid drainage solutions (Ur dump, Salair): Electrical resistivity tomography and hydro-geochemical data: Russian Geology and Geophysics, **57**, 617–628.

Parasnis, D., 2013, Mining geophysics (Vol. 3): Elsevier.

Parbhakar-Fox, A., and Lottermoser, B., 2017, Principles of sulfide oxidation and acid rock drainage: Environmental Indicators in Metal Monong, Springer, Cham.

Placencia-Gómez, E., Parviainen, A., Hokkanen, T., and Loukola-Ruskeeniemi, K., 2010, Integrated geophysical and geochemical study on AMD generation at the Haveri Au–Cu mine tailings, SW Finland: Environmental Earth Sciences, **61**, 1435–1447.

Ptitsyn, A.B., 2006, Theoretical Geochemistry: *Ed.* I.D. Ryabchikov (GEO, Novosibirsk, 2006). (in Russian)

Ptitsyn, A.B., Markovich, T.I., Pavlyukova, V.A. and Epova, E.S., 2007, Modeling cryogeochemical processes in the oxidation zone of sulfide deposits with the participation of oxygen-bearing nitrogen compounds: Geochemistry International, **45**, 726–731.

Rucker, D.F., Glaser, D.R., Osborne, T., and Maehl, W.C., 2009, Electrical resistivity characterization of a reclaimed gold mine to delineate acid rock drainage pathways: Mine Water and the Environment, **28**, 146–157.

Semenov, A.S., Novozhilova, M.E., and Veshev, A.V., 1957, Changing natural electric field in the Earth: Questions of Ore Geophysics, **1**, 83–113. (in Russian)

Shesternev, D.M., 2001, Cryohypergenesis and geotechnical properties of cryolithozone rocks: Novosibirsk Publishing House of the SB RAS. (in Russian)

Sveshnikov, G.B., 1967, Electrochemical processes at sulfide deposits. (in Russian)

Tataurov, S.B., 2008, Transformation and processing of gold-bearing raw materials in conditions of permafrost zone. Moscow: Gornaya Kniga.

Vernadsky, V.I., 2012, The biosphere: Science and Business Media.

Wells, C.B., 1978, Electrolytic conductivity of soil solutions and wares: conversions from field to standard temperatures: Division of Soils Technical Paper, **37**, 1–17.

Yurkevich, N.V., Saeva, O.P., Karin, Y.G., 2015, Geochemical anomalies in two sulfide-bearing waste disposal areas: Fe, Cu, Zn, Cd, Pb, and As in contaminated waters and snow, Kemerovo and Chelyabinsk regions, Russia: Toxicological and Environmental Chemistry, **97**, 76–89.

Yurkevich, N., Bortnikova, S., Olenchenko, V., Abrosimova, N., Saeva, O., and Karin, Y., 2017, Study of water-rock interaction in sulfide mining tailings using geochemical and geoelectrical methods: Procedia Earth and Planetary Science, **17**, 112–115.

Yurkevich, N.V., Abrosimova, N.A., Bortnikova, S.B., Karin, Y.G., and Saeva, O.P., 2017, Geophysical investigations for evaluation of environmental pollution in a mine tailings area: Toxicological and Environmental Chemistry, **99**, 1328–1345.

Yuval, D., and Oldenburg, W., 1996, DC resistivity and IP methods in acid mine drainage problems: Results from the Copper Cliff mine tailings impoundments: Journal of Applied Geophysics, **34**, 187–198.

Zerkalov, V.I., 1959, New minerals in ores of the Ur deposits: Salair, Vestnik.

Zhang, D.W., Chen, L., and Liu, S.Y., 2012, Key parameters controlling electrical resistivity and strength of cement treated soils: Journal of Central South University, **19**, 2991–2998.

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