DOI: 10.31897/PMI.2020.3.379

UDC 504.064.2: 550.837.21

Study of the technogenesis of the Degtyarsky mine by audio-magnetotelluric express sounding

Vadim A. DAVYDOV
Bulashevich Institute of Geophysics UB RAS, Yekaterinburg, Russia

The audio-magnetotelluric express sounding was performed at four sections crossing the mine field of the currently not functioning Degtyarsky mine. Field measurements were carried out by a universal broadband receiver "OMAR-2m" with active electromagnetic field sensors developed at the Institute of Geophysics UB RAS. Based on the obtained data, deep sections of the electrophysical parameters of the medium – apparent resistivity and effective longitudinal conductivity – are drawn. The nature of the geoelectric structure of the section allows mapping of the major lithochemical contamination plume and identifying the tectonic disturbance zones that drain aggressive mine waters. The mine waters of the Degtyarsky mine are a source of dangerous technogenic pollution. Despite the neutralization of surface runoff, underground routes of acidic water migration occur along tectonic cracks, primarily in the zone of the regional Serovsko-Mauksky fault. Tectonic zones in the mine area contain contaminated fissure-vein water, which is transited at a depth of 70 to over 200 m. Discharging ascending springs of such waters can be located at a great distance from controlled hydrological objects and pollute sources of drinking and household water supply. Urban development in the western and eastern parts of Degtyarsk does not fall within the distribution zone of polluted water. The southern part of the city is located beyond the watershed of the mine water flow area, but a danger of local contamination by tectonic disturbance zones remains possible. The worst environmental situation is observed in the northern outskirts of Degtyarsk, which falls into the area of heavy pollution of underground and surface waters. Besides, acidic fumes from the flooded Kolchedanny quarry can affect the health of city residents when emitted to the atmosphere.

***Key words*:** geoecology; mine drainage; technogenic pollution; AMS; longitudinal conductivity; tectonic zones

***How to cite this article*:** Davydov V.A. Study of the technogenesis of the Degtyarsky mine by audio-magnetotelluric express sounding. Journal of Mining Institute. 2020. Vol. 243, p. 379-387. DOI: 10.31897/PMI.2020.3.379

Introduction. Technogenesis is commonly understood as a set of various processes that change the natural environment under the influence of human activity. The largest environmental transformations are caused by the ore mining industry. The active stage of ore mining technogenesis, associated with the removal and movement of large masses of rocks, occurs during the development of deposits. Mining operations change the structure and chemical composition of the lithosphere, as well as pollute the atmosphere and natural waters. As a result, extensive litho-, atmo-, and hydrochemical pollution plumes are formed [1]. After the mine closure, a post-operational passive stage of technogenesis occurs, characterized by a lower degree of impact, but much longer duration.

In the mining industry of the Urals, a special place is taken by pyrite deposits. Ore minerals undergo hypergenic changes when the hard-to-dissolve sulfides are oxidized to well-soluble sulfates in the presence of free oxygen. A sharp decrease in the pH of water, accompanied by an increase in the redox potential, is the result of these reactions that leads to the transformation of natural geochemical processes. The consequence is a change in the chemical composition of natural waters, technogenic migration of ore elements and environmental pollution by heavy metals [12]. These processes continue for a long time after the closure of mining enterprises. The purpose of the work is to determine the scale of pollution from the currently non-functioning Degtyarsky mine in the Middle Urals. The main task is to study the features of the geoelectric structure of the mine field section using magnetotelluric technologies.

Problem statement. The Degtyarskoye copper-pyrite deposit, known since 1888, occupies the central district of the town of Degtyarsk. Initially, the Istokinsky brown iron ore (limonite) mine was developed here; in 1906, sulfide ores were discovered in the underlying strata. The deposit is located in the most narrowed part of the Tagilo-Magnitogorsky downfold and is represented by a

DOI: 10.31897/PMI.2020.3.379

single ore body lying in the sidewall of the Serovsko-Mauksky fault. The pyrite deposit lies in accordance with the host volcanogenic and volcanogenic-sedimentary rocks of the Degtyarskaya suite, saturated with pyrite inclusions. The rocks have a rhythmic structure, geochemical and ore zoning indicates that the thickness is tilted to the West. In the East, the Degtyarskaya suite is permeated by rhyolite bodies of the subvolcanic complex and is bordered by granitoids of the Novoalexeyevsky massif.

Westward from the ore deposit, a fault zone contacts with igneous rocks of the Tagilsky downfold [3]. In the fault zone, serpentinites, marbled limestones, shales, and other rocks are randomly alternating with each other. All these formations are characterized by intense block fragmentation, forming a giant tectonic breccia (zone of polymictic melange). The fault zone closely approaches the ore body and cuts off the ore-containing contact at deep horizons. The average thickness of the ore body is over 10 m, the length is ca. 5 km, the strike is submeridional with a fall to the East at an angle of 55-90°. Massive and impregnated ores are the two main types of pyrites. The main ore minerals are pyrite, chalcopyrite, and sphalerite. The ore outcrop is represented by limonites of the oxidation zone or "iron hat" with a thickness of 10-25 m. In the northern and central parts of the deposit, the "iron hat" was completely mined by quarries. The Degtyarsky underground mine operated from 1914 to 1995 with a maximum depth of 610 m. Before the closure of the mine, eight shafts were collapsed, one shaft was filled in, and four shafts were preserved: Kapitalnaya-1, Kapitalnaya-2, Srednyaya, and Yuzhnaya (Fig.1).

The Degtyarskoye field is located in a deep swampy depression with absolute levels of 323-355 m, descending in the submeridional northern direction. In the West and East, the lowland is surrounded by a chain of hills with heights of 360-488 m. Within the depression, along the zone of the Serovsko-Mauksky fault, the Degtyarka River flows, the course of which has been greatly changed during the period of mining operations. In the North, the mine field crosses the Istok River in the latitudinal direction that flows from the Ikbulat Lake and flows into the Degtyarka River. South of the mine field, the Vyazovka River, a tributary of the Chusovaya River, flows in a sublatitude direction [10].

According to the conditions of accumulation and circulation, the underground water of the district is classified as fissure and fissure-vein. Despite the complexity of the structure of the filtration flow in undisturbed conditions, the underground water level usually repeats the smoothed relief of the Earth's surface. Underground watersheds are a reflection of surface ones, and the discharge of underground flow is carried out in the local river network – the rivers Degtyarka, Istok, and Vyazovka. During the operation of the mine, constant drainage of 200-300 m^3/h was carried out, which led to the formation of a stable depression funnel with an area of more than 5 km^2.

Within the contour of the depression of the Degtyarskoye field, a man-made aeration zone was formed with a system of drainage channels connecting the surface with underground mine workings. Active aerogenic circulation penetrated deep horizons that were isolated from atmospheric air penetration under natural conditions. A lithochemical plume, enriched with the dispersed sulfides and easily soluble technogenic hydrosulfates of iron, copper, zinc, and others, was formed on the surface and in the technogenic aeration zone. During the four years after pumping shutdown, the underground workings had been being completely flooded. The release of mine water occurred in the Kolchedannaya quarry, and, after its filling, in the Istok River. Mine water discharge is a technogenic spring, which regime is influenced by climatic factors and has a flow rate that is many times higher than natural analogues (up to 30-60 l/s). It is provided by the infiltration of atmospheric precipitation within the drainage area of underground mine workings from an area of at least 2 km^2, which provides a constant flow of mine water [13].

The active oxidation of sulfides and sulfuric acid leaching of ore-containing rocks determined the chemical composition of water. According to hydrogeological data, the drainage waters of the Degtyarsky mine are classified as sulfate magnesium-calcium-ferruginous, acidic and ultra-acidic,

DOI: 10.31897/PMI.2020.3.379

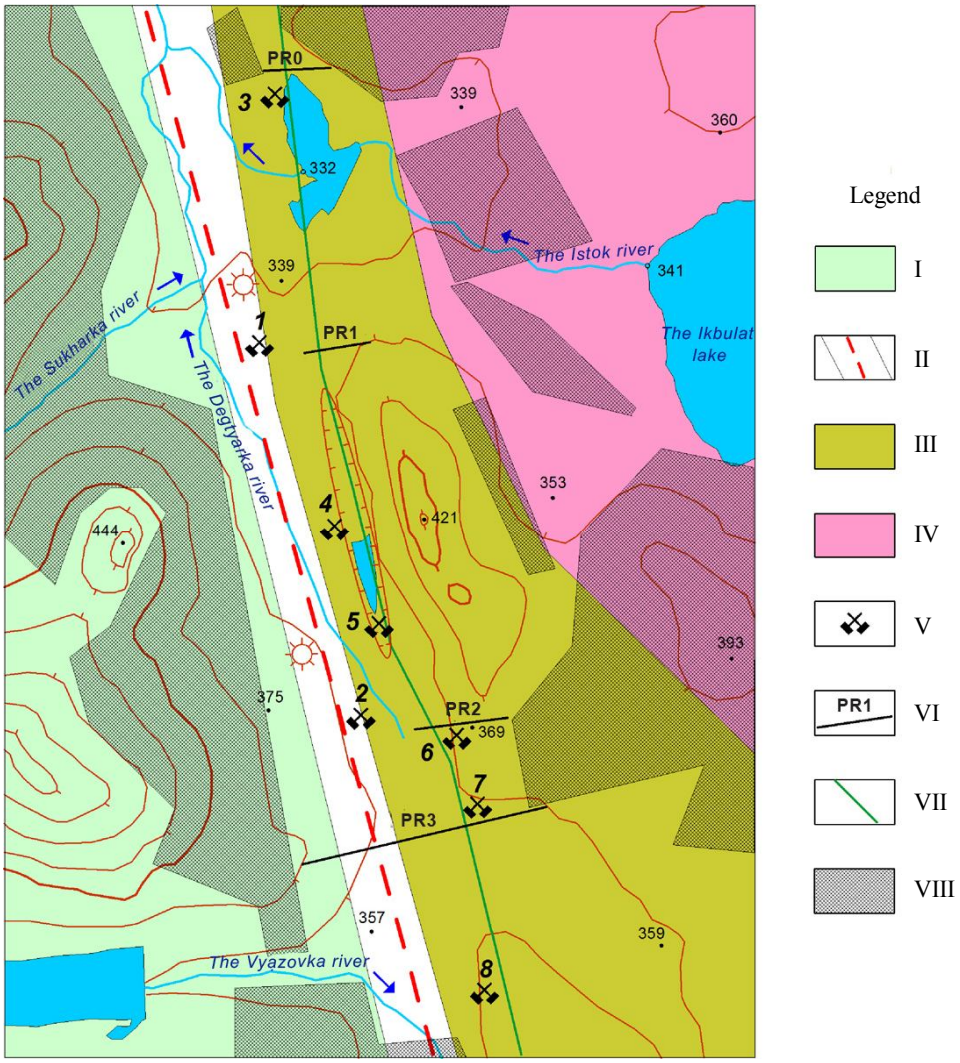


Fig.1. Schematic map of the Degtyarsky mine

I – igneous rocks of the Tagilsky downfold (basalts, diorites, and gabbro); II – zone of the Serovsko-Mauksky fault with polymictic melange; III – volcanogenic-sedimentary rocks of the Degtyarsky suite (tuff-sandstones, basalts, and tuffs); IV – Degtyarsky subvolcanic complex (rhyolites, plagiogranites); V – closed mines (1 – Kapitalnaya-1; 2 – Kapitalnaya-2; 3 – Kolchedannaya; 4 – Srednyaya; 5 – Pervomayskaya; 6 – Moskva; 7 – Komsomolskaya; 8 – Yuzhnaya); VI – PR1 geophysical sections; VII – projection of the ore outcrop; VIII – residential districts

briny, with mineralization of 3-8 g/l and pH = 2.5-3.6 [4]. Such waters have very low electrical resistivity values (< 1 Ohm·m), so the areas of their distribution should be confidently distinguished by electrical exploration methods.

Electromagnetic sounding allows tracing the zones of penetration and drainage of mine water into the host rocks by electrical conductivity anomalies. The study of the electrophysical properties of the geological section will help to identify the main plumes of aggressive underground water and determine the danger of man-made pollution of the urban area.

Methodology. The audio-magnetotelluric sounding (AMS), applied to study the nature of the geoelectric section, has the necessary transmission distance and has proven itself positively in the study of groundwater [7, 15, 18, 19] and sulfide mineralization [16, 17]. Field measurements were carried out in the express version of AMS with dual-channel universal receiver "OMAR-2m", designed at the Institute of Geophysics UB RAS [9].

Registration of the natural electromagnetic field was conducted in the frequency range of 100-15000 Hz on latitudinal sections in 20 m increments. The duration of continuous recording at the point was 2-3 minutes. To observe the horizontal component of the H_x magnetic field, an active inductive sensor with a linearized amplitude-frequency response and variable sensitivity was used.

DOI: 10.31897/PMI.2020.3.379

The electrical component E_y was measured using an outspread capacitive line with a pre-amplifier [6]. The ratio of the amplitude of the electrical component of the signal to the orthogonal magnetic component determines the impedance of the medium $Z = E_y / H_x$, which is proportional to the electrical resistivity of rocks. The apparent values of specific electrical resistivity (SER) were calculated using the formula adopted in magnetotelluric studies [2]:

$$\rho_t = (1/2\pi f\mu)|Z|^2,$$

where f is the signal frequency, Hz; $\mu \approx \mu_0 = 4\pi \cdot 10^{-7}$ is the magnetic permeability of the medium, H/m.

The stages of desk-study processing of the audio-magnetotelluric data included:

• filtering of electromagnetic interference with a frequency of 50 Hz and its harmonics;

• obtaining signal spectra using fast Fourier transform;

• restoration of the real spectral distribution of signal amplitudes taking into account the nonlinearity of the characteristics of end-to-end measuring channels;

• determination of spectral relations $E_y(f)/H_x(f)$ to obtain the longitudinal impedance of the medium $Z(f)$;

• the calculation of the apparent resistivity (AR) to produce frequency curves $\rho_t(f)$;

• transformation of frequency curves into a deep section of resistivity $\rho_t(h)$, using the original conversion algorithm [8];

• recalculation and drawing of the section of the effective longitudinal conductivity S_{ef}.

Results. The marking of research sections is carried out in the sublatitudinal direction, intersecting the major geological structures. In total, four sections were passed in different sections of the ore field. Audio-magnetotelluric sounding is a fairly deep technique of geophysical research. The frequency range in which the measurements were made provides the information on the section at a depth of ten to several hundred meters [5]. However, the resolution of the AMS decreases with depth, so the depth of research was limited to 200-300 m to maintain a high level of detail.

The features of the geoelectric structure of the mine territory are due to the difference between the SER of rocks and ores, waterlogging, tectonics, and undermining. The study of the electrophysical properties of the section in the zone of technogenic impact of mine waters was started from the northern part of the mined field, near the flooded Kolchedannaya quarry. The section PR0 crosses the northern part of the artificial brown-colored lake with a persistent smell of sulfuric acid. In the southern part of the former quarry, mine water from the Degtyarsky mine and the sub-basement water from the Kapitalnaya-1 mine outflows constantly. From the East, the Istok River flows into the lake and, when mixed with mine waters, forms a common runoff with water mineralization levels of 3.7-12.8 g/l and pH = 2.3-3.3 [16].

Tuffaceous sandstones and green-stone shales are the major host rocks along the line of the PR0 section. Surface clay deposits are characterized by the lowest resistivity values (10-20 Ohm·m), with an increasing proportion of the fractions of sand and rock debris, the resistivity of loose rocks increases to 100-150 Ohm·m. Bedrock has higher electrical resistivity, varying from 150-200 to 1000-3000 Ohm·m (Fig.2).

Taking into account the lateral influence of the flooded quarry with a depth of more than 70 m, the obtained electrical resistivity is somewhat underrated. However, by the type of the KS section one can say that the penetration of acidic waters into the bedrock reaches a depth of more than 150 m from the daylight surface. Through tectonic cracks pollution can reach even deeper horizons. Tectonic disturbances in the geoelectric section are usually characterized by linear low-resistance anomalies. At the same time, the shape of abnormal zones is better distinguished on sections of longitudinal conductivity.

Due to the increase in the volume of cracks filled with water, tectonic zones are marked by increased electrical conductivity (from 0.5 S or more). In the section of effective longitudinal con-

DOI: 10.31897/PMI.2020.3.379

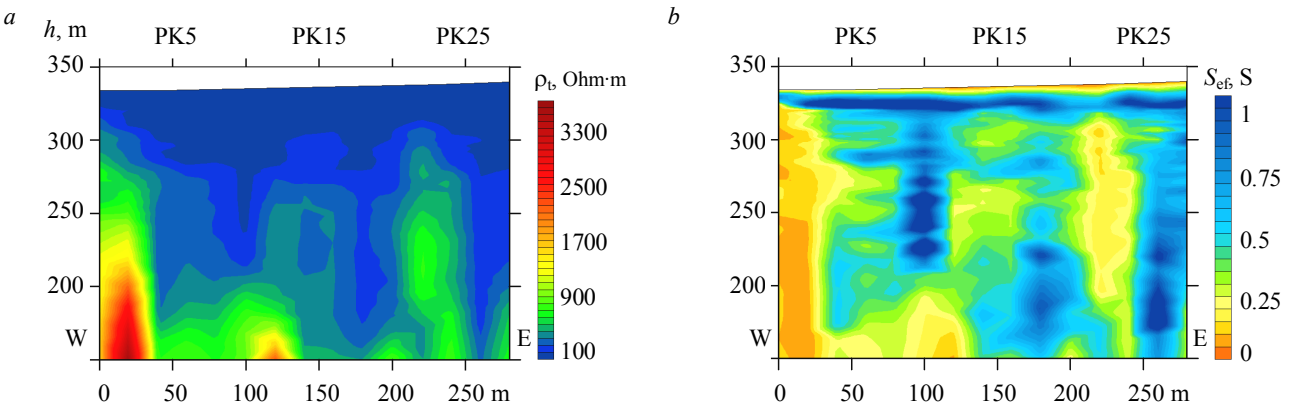


Fig. 2. Deep sections of electrophysical parameters on the PR0 profile in the area of the Kolchedannaya quarry: *a* – apparent resistivity; *b* – effective longitudinal conductivity

ductivity (Fig.2, *b*), several abnormally conducting structures are distinguished. Of these, three subvertical linear anomalies located in the area of PK10, PK18, and PK27 pickets can be associated with tectonic zones. Horizontal electrical conductivity anomaly at the depth of 5-15 m corresponds to temporary perched ground water. Technogenic pollution spreads westward in the near-surface layer of soil water, coming back into the Istok River. A neutralization station is situated downstream, at the confluence of the Istok and Degtyarka. The total river and mine runoff is neutralized here by lime milk, which reduces the pH to 6.5-8.5. After neutralization, the waste water flows into the Yelchovka River, next to the settling pond.

Water from the Yelchovsky pond is discharged into the Volchikhinskoye reservoir, which is the main source of water supply in Yekaterinburg. The environmental situation with the surface flow is under control – the water condition in the rivers Degtyarka, Istok, and Yelchovka, as well as in the settling pond, is being monitored. However, uncontrolled migration routes of polluted water through tectonic zones identified by electrophysical sections are possible (Fig.2). Cracks of tectonic genesis contain fractured-vein water, which is transited in the lower part of the hydrogeological section at a depth of 100-250 m. Areas of discharge of such waters may be located outside of controlled hydrological objects, in the direction of the Volchikhinsky reservoir.

The next research section PR1 is located in the vicinity of the Kapitalnaya-1 mine, 1 km southward of PR0. It runs along the northern slope of the Labaz mountain, near the northern part of the quarry abandoned after mining of the "iron hat". In the initial part of the section, surface failures were recorded due to the collapse of underground workings. In this section, the RES of bedrock has small values (50-400 Ohm·m), the increase in resistances to 1000-6000 Ohm·m is observed in the second half of the section (Fig.3).

Electrical resistivity can vary greatly even in rocks of the same composition and origin. This variability is due to hydrothermal changes near ore zones, scattered sulfide inclusions, fracturing and humidity of rocks, as well as mineralization of pore moisture. Acid pollution, according to the resistivity measurements, embraces a layer of about 100 m from the daily surface. In the section of effective longitudinal conductivity (Fig. 3, *b*), a characteristic tectonic disturbance (PK4), known from the data of the mine documentation as a thrust dislocation that crosscuts the ore body, is well distinguished. The near-surface horizontal conducting zone of up to 0.7 S (PK0-PK5) is apparently associated with the sub-basement waters of the Kapitalnaya-1 mine dump. Zones with weakly increased electrical conductivity (0.2-0.3 S) are caused by local bedrock fracturing.

The PR2 research section is located 1.5 km southward of PR1 and runs along the southern slope of the Labaz (Karaulnaya) mountain. Its beginning is 300 m eastward of the Kapitalnaya-2 mine, at approximately the same distance southward of the flooded part of the quarry where the "iron hat" of the Degtyarskoye deposit was mined. In the surrounding area, intensive work was carried out at all horizons but no failures of underground workings were detected along the observation

DOI: 10.31897/PMI.2020.3.379

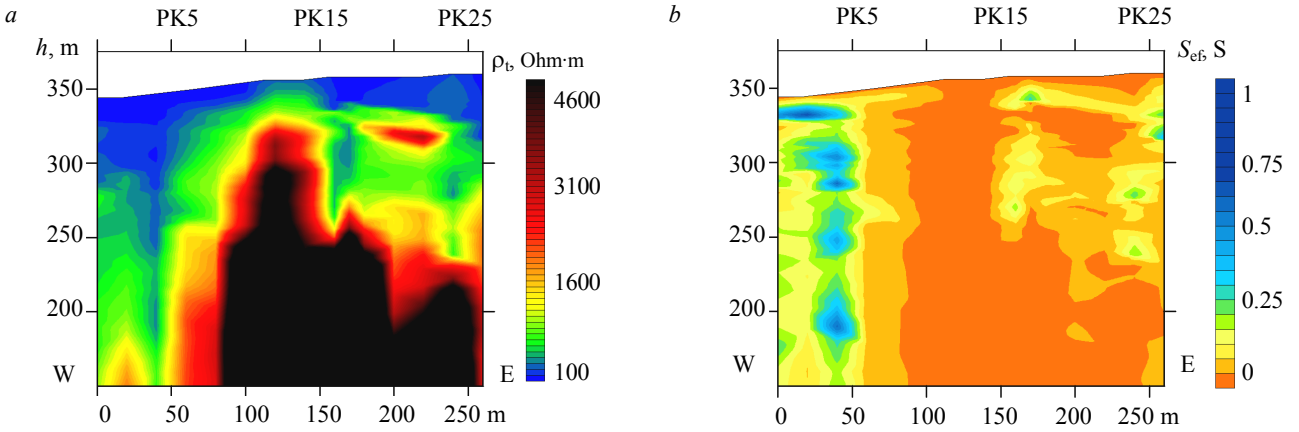


Fig. 3. Deep sections of electrophysical parameters on the PR1 section in the area of the Kapitalnaya-1 mine:
a – apparent resistivity; *b* – effective longitudinal conductivity

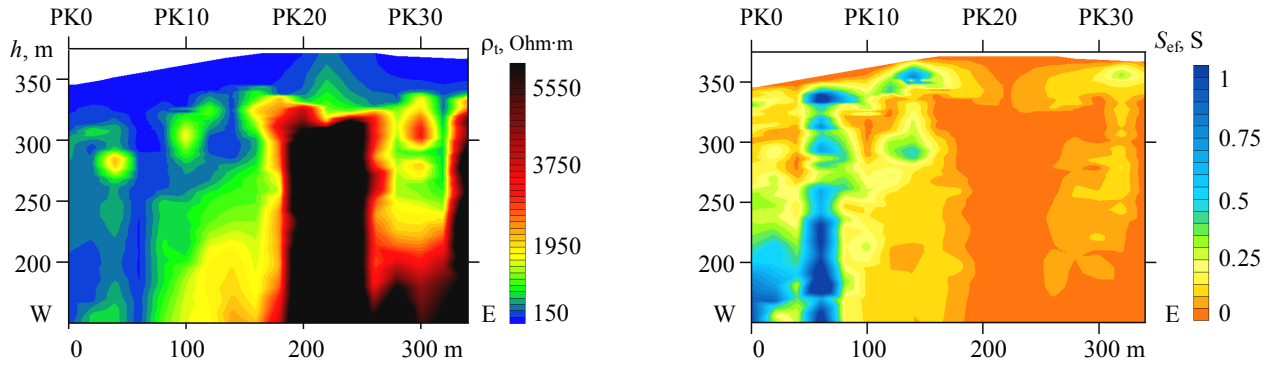


Fig.4. Deep sections of electrophysical parameters on the PR0 in the area of the Moskva mine:
a – apparent resistivity; *b* – effective longitudinal conductivity

line. The projection on the surface of the eastern boundary of the mining area approximately corresponds to the PK18 section. The electrical characteristics of the undermined area (PK0-PK18) and the area not affected by mining operations (PK18-PK34) are very different (Fig.4).

At the first pickets, the resistivity of the bedrock is 100-500 Ohm·m, increasing to 1000-1500 Ohm·m in the middle of the section at deep horizons. When moving to the area of undisturbed monolithic rocks, resistivity increases sharply up to 5000-8000 Ohm·m. On the site that was subjected to underground work, the main area of acidic water circulation corresponds to the underground horizon of 70 m (abs. level of 290 m). Judging by the section of longitudinal conductivity, the upper horizons are additionally fed from the lower horizons (130 m and 190 m), similar to the situation observed at the nearest Krylatovsky mine [11]. Flows between horizons are carried out along the vertical shafts of liquidated mines and in the tectonic zone (PK6). The ridge of the Labaz mountain and its gently sloping continuation (PK22) serves as the watershed of the Degtyarka River and the Ikbulat Lake; so, groundwater contamination of an urban area eastward of the mountain does not occur (Fig.1).

The PR3 section is the longest (1100 m) and passes through all the main geological structures of the Degtyarskoye ore field. The section is located on the southern section of the Degtyarskoye field, passing near the Komsomolskaya mine. The beginning of the section consists of igneous rocks of the Tagilsky downfold, belonging to the Zyuzelskaya suite. After that, the section crosses from West to East the zone of the Serovsko-Mauksky fault, behind which the ore-bearing volcanic-sedimentary rocks of the Degtyarskaya suite of the East Ural uplift lie. All the mentioned structures are well displayed on the sections of geoelectric parameters (Fig.5).

DOI: 10.31897/PMI.2020.3.379

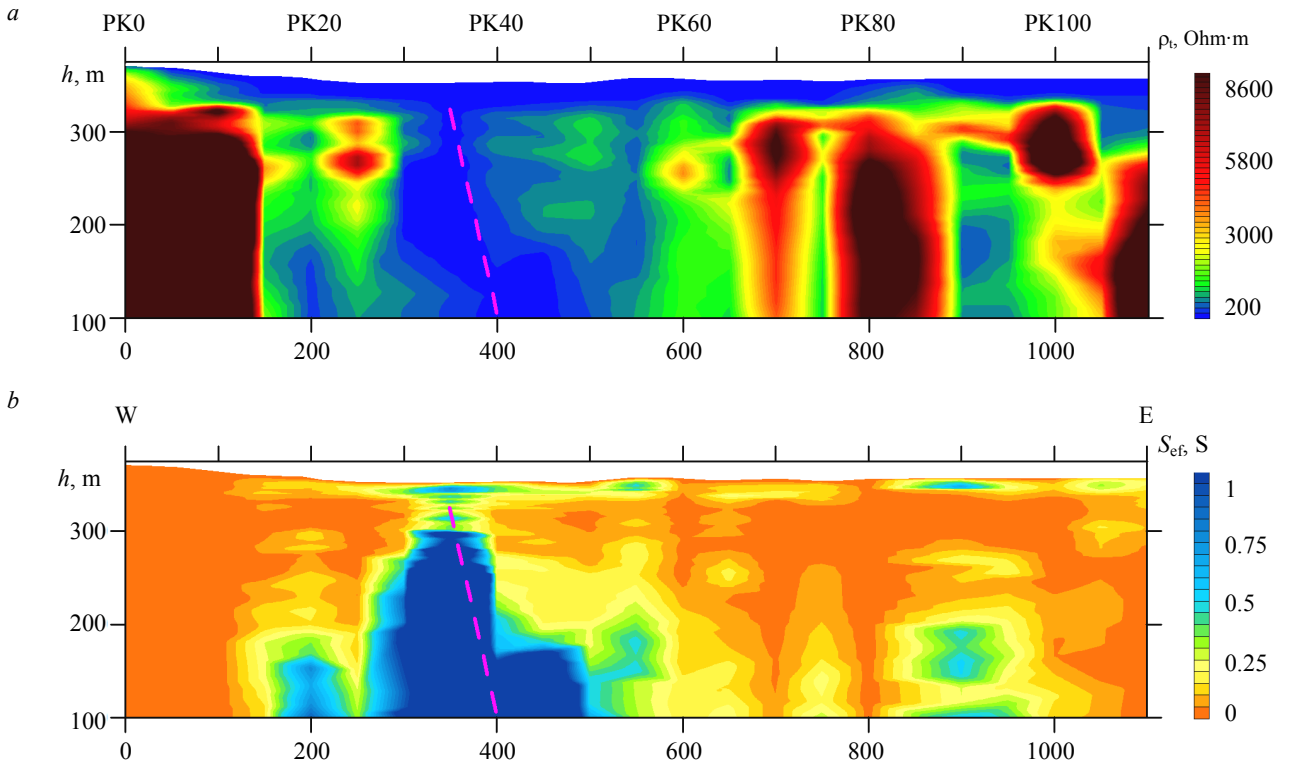


Fig.5. Deep sections of electrophysical parameters along the PR3 section in the area of the Komsomolskaya mine: *a* – apparent resistivity; *b* – effective longitudinal conductivity; dotted line shows the axis of the Serov-Mauk fault

The volcanites of the Zyuzelskaya suite (PK0-PK30) are distinguished by the highest RES on the section, their resistivity varies depending on the fracture from 1000 to 10000 Ohm·m. The zone of influence of the Serovsko-Mauksky fault (PK30-PK58), which is characterized by the lowest values of RES (up to 50 Ohm·m), is most well defined, and the eastern fault slope at an angle of about 70° is quite clearly defined. The outcrop of the ore body to the surface is confined to a swampy lowland and was located in the range of the PK64-PK65 points; at present, the swamp is almost completely covered with lime production waste. The ore body is not identified by the geoelectric section but a vertical low-resistance anomaly associated with the near-ore tectonic zone is observed at the PK75 picket, which has already been shown on the PR1 and PR2 sections. The specific electrical resistivity of rocks of the Degtyarskaya suite are sufficiently sustained and make up 3000-8000 Ohm·m.

In the area of PK88-90, a deep anomaly of low resistivity occurs probably due to strong rock fracturing. This zone has an eastward drop at an angle of about 80° and is characterized by the electrical conductivity of up to 1 S, which indicates its water saturation. The regional Serov-Mauk fault is the most conductive object of the section, which effective longitudinal conductivity is from 1 to 6.5 S. Given such high values, we can conclude that there is a clear inflow of polluted mine water into the fault zone, with the possibility of their further migration over long distances.

Analyzing the results of audio-magnetotelluric sounding, taking into account the available data on the structure of the area, a schematic hydrogeological section of the current state of the Degtyarsky ore field was drawn (Fig.6).

The obtained electrophysical parameters allow to determine the boundary between active and passive water exchange. The zone of active water exchange is characterized by a constant oxygen supply leading to the oxidation of sulfides and sulfuric acid leaching of rocks. Due to this, the acidity of ground water remains at a high level, and mineralization increases due to the penetration of atmospheric waters and the dissolution of accumulated sulfates, which leads to a general decrease in the electrical resistivity of the medium. At a greater depth, in the zone of reduced water exchange, leaching processes are poorly developed and the electrophysical properties of rocks are close to

DOI: 10.31897/PMI.2020.3.379

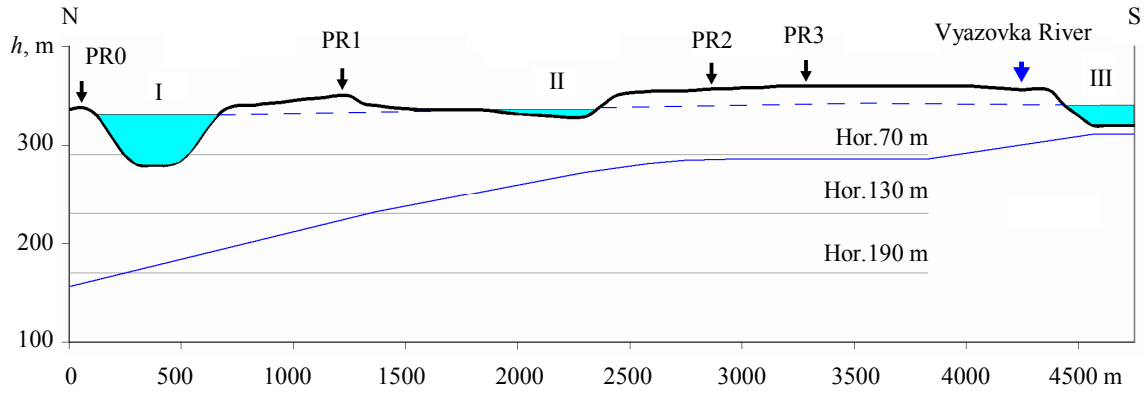


Fig. 6. Schematic longitudinal section in the center of the Degtyarsky mine field
I – flooded Kolchedannaya quarry; II – "iron hat" mining site;
III – flooded limestone quarry (the Mednoe Lake); solid blue line – active water exchange border; dotted line – ground water level

natural values. In the southern part of the mine field, the depth of active water exchange is 70-80 m, increasing in the central area to 100-150 m and reaching the maximum depth of 200 m in the northern part. Outside the field, the hydrogeological situation is gradually returning to its natural state.

Conclusions. The Degtyarsky mine drainage is a source of dangerous technogenic pollution of the environment and water resources. Despite the neutralization of surface runoff, underground routes of acidic water migration occur along tectonic cracks, primarily in the zone of the regional Serovsky-Mauksky fault. Tectonic zones in the mine area contain contaminated fissure-vein water, which is transited at a depth of 70 to over 200 m. Discharging ascending springs of such waters can be located at a great distance from controlled hydrological objects and pollute sources of drinking and household water supply.

Urban development in the western and eastern parts of Degtyarsk fits closely, but does not fall within the distribution zone of polluted water. The southern part of the city is located beyond the watershed of the mine water flow area, however, there is a danger of local contamination by tectonic disturbance zones. The worst environmental situation is observed in the northern outskirts of Degtyarsk- falling into the area of heavy pollution of underground and surface waters. In addition, acidic fumes from the flooded Kolchedannaya quarry can affect the health of city residents when emitted to the atmosphere.

REFERENCES

1. Androsova N.K. Geochemistry of technogenesis in areas of working out of mineral deposits. *Zapiski Gornogo instituta*. 2013. Vol. 203, p. 35-38 (in Russian).

2. Berdichevskii M.N., Dmitriev V.I. Models and methods of magnetotellurics. Moscow: Nauchnyi mir, 2009, p. 680 (in Russian).

3. Kalugina R.D., Kopanev V.F., Storozhenko E.V., Lukin V.G., Stepanov A.E., Rapoport M.S., Iyasova G.A., Suslov D.L., Mikhaleva E.N., Shub I.Z., Glazyrina N.S., Stratovich V.I., Chernyak Z.B., Mikhailov A.P., Gerasimenko B.N. State geological map of the Russian Federation. Scale 1:200000. The Middle Urals Series. List O-41-XXV. Explanatory note. Moscow: Moskovskii filial FGBU "VSEGEI", 2017, p. 156 (in Russian).

4. Gryaznov O.N., Elokhina S.N. Geoecological problems of mining technogenesis in the Urals. *Izvestiya Uralskogo gosudarstvennogo gornogo universiteta*. 2017. N 2 (46), p. 28-33. DOI: 10.21440/2307-2091-2017-2-28-33 (in Russian).

5. Davydov V.A. Audio-frequency magnetotelluric survey on the run. *Geofizika*. 2014. N 2, p. 47-53 (in Russian).

6. Davydov V.A. New electromagnetic sensors for mid-frequency electrical exploration. *Datchiki i sistemy*. 2017. N 11, p. 58-62 (in Russian).

7. Davydov V.A. Application of audiomagnetotellurics express-sensing in the study of the engineering-geological conditions deposits. *Razvedka i okhrana nedr*. 2016. N 6, p. 32-36 (in Russian).

8. Davydov V.A. Audio magnetotelluric data transformation using a priori information. *Geofizicheskie issledovaniya*. 2016. Vol. 17. N 4, p. 57-66 (in Russian).

9. Davydov V.A. Universal field geophysical receiver OMAR-2. *Pribory i tekhnika eksperimenta*. 2016. N 6, p. 127-128. DOI:10.7868/S0032816216060252 (in Russian).

10. Elokhina S.N. Role of technogenesis in the structural transformation of the underground hydrosphere. *Geoekologiya. Inzhenernaya geologiya, gidrogeologiya, geokriologiya*. 2007. N 6, p. 494-505 (in Russian).

11. Elokhina S.N., Arzamastsev V.A., Borich S.E., Sotova E.M., Shchapov V.A. Zoning of natural-technogenic hydrogeological systems (using Krylatsky mine as an example). *Izvestiya vuzov. Geologiya i razvedka*. 2010. N 1, p. 57-66 (in Russian).

12. Opekunov A.Yu., Opekunova M.G. Technogenic geochemistry in the development of Sibai chalcopyrite field. *Zapiski gornogo instituta*. 2013. Vol. 203, p. 196-204 (in Russian).

13. Elokhina S.N., Kindler A.A., Sharaev R.N., Tsaregorodtseva A.A. Parameters of the mining post-operational technogenesis in the zone of influence of the Degtyarsky mine. Sergeevskie chteniya. Ustoichivoe razvitie: zadachi geoekologii (inzhenerno-geologicheskie, gidrogeologicheskie i geokriologicheskie aspekty). Moscow: Rossiiskii universitet druzhby narodov, 2013, p. 249-254 (in Russian).

14. Singh S., Maurya V.P., Singh R.K., Srivastava S., Tripathi A., Adhikari P.K. Audio-magnetotelluric investigation of sulfide mineralization in Proterozoic – Archean greenstone belts of Eastern Indian Craton. *Journal of Earth System Science*. 2018. Vol. 127(34), p. 1-18. DOI: 10.1007/s12040-018-0938-z

15. Tarabees E.A., Tewksbury B.J., Mehrtens C.J., Younis A. Audio-magnetotelluric surveys to constrain the origin of a network of narrow synclines in Eocene limestone, Western Desert, Egypt. *Journal of African Earth Sciences*. 2017. Vol. 136, p. 168-175. DOI: 10.1016/j.jafrearsci.2017.03.001

16. Elokhina S.N., Ryzhenko B.N. Secondary mineral-forming processes in natural-anthropogenic hydrogeological systems at sulfide deposits. Simulation of the origin of the phase $(Fe,Mg)SO_4\ 7H_2O$ in the course of sulfide oxidation at the Degtyarka copper sulfide deposit. *Geochemistry International*. 2014. Vol. 52. N 2, p. 162-177. DOI: 10.1134/S0016702914020050

17. Lahti I., Kontinen A., Nykänen V. AMT survey in the Outokumpu ore Belt, Eastern Finland. *Exploration Geophysics*. 2019. Vol. 50(4), p. 351-363. DOI: 10.1080/08123985.2019.1606200

18. Carlson N.R., Paski P.M., Urquhart S.A. Applications of controlled source and natural source audio-frequency magnetotellurics to groundwater exploration. Symposium on the Application of Geophysics to Engineering and Environmental Problems 2005. Society of Exploration Geophysicists, 2005, p. 585-595. DOI: 10.4133/1.2923511

19. Blake S., Henry T., Muller M.R., Jones A.G., Moore J.P., Murray J., Campanyà J., Vozar J., Walsh J., Rath V. Understanding hydrothermal circulation patterns at a low-enthalpy thermal spring using audio-magnetotelluric data: A case study from Ireland. *Journal of Applied Geophysics*. 2016. Vol 132, p. 1-16. DOI: 10.1016/j.jappgeo.2016.06.007

Author **Vadim A. Davydov,** *Candidate of Geological and Mineralogical Sciences*, *Senior Researcher*, *davyde@yandex.ru* (*Bulashevich Institute of Geophysics UB RAS*, *Yekaterinburg*, *Russia*).

The paper was received on 31 October, 2019.
The paper was accepted for publication on 4 March, 2020.