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Forecasting of mining and geological processes based on the analysis of the underground space of the Kupol deposit as a multicomponent system (Chukotka Autonomous Region, Anadyr district)

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Abstract. The underground space of the Kupol deposit is analyzed as a multicomponent system – rocks, underground water, microbiota, gases (including the mine atmosphere) and supporting structures – metal support and shotcrete (as an additional type of barring) and also stowing materials. The complex of host rocks is highly disintegrated due to active tectonic and volcanic activity in the Cretaceous period. The thickness of sub-permafrost reaches 250-300 m. In 2014, they were found to contain cryopegs with abnormal mineralization and pH, which led to the destruction of metal supports and the caving formation. The underground waters of the sub-permafrost aquifer are chemically chloride-sulfate sodium-calcium with a mineralization of 3-5 g/dm^3. According to microbiological analysis, they contain anaerobic and aerobic forms of microorganisms, including micromycetes, bacteria and actinomycetes. The activity of microorganisms is accompanied by the generation of hydrogen sulfide and carbon dioxide. The main types of corrosion – chemical (sulfate and carbon dioxide), electrochemical and biocorrosion are considered. The most hazardous is the biocorrosion associated with the active functioning of the microbiota. Forecasting and systematization of mining and geological processes are carried out taking into account the presence of two zones in depth – sub-permafrost and below the bottom of the sub-permafrost, where mining operations are currently underdone. The importance of assessing the underground space as a multicomponent environment in predicting mining and geological processes is shown, which can serve as the basis for creating and developing specialized monitoring complex in difficult engineering and geological conditions of the deposit under consideration.

***Key words*:** multicomponent system; underground space; sub-permafrost; cryopegs; gases; microbiota; biocorrosion; safety

Introduction. The theory and practice of the world experience in the development and use of underground space (US) of mining regions and megacities indicate that the choice of development technology is usually based on a schematic account of rocks (soils) in the cut and justification of the stress-strain state (SSS) of the massive (thickness) using a linear, and more often nonlinear (elastic-plastic) problem of assessing the workings stability during their construction and operation. However, the comprehensive analysis of the occurrence and development of emergency and pre-emergency situations in solving the problem in European countries and countries of Southeast Asia dictates the need for a fundamental change in such a concept, as it does not meet the complexity of real conditions while solving problems of improving safety and operational reliability, and also reducing the risk of underground mining, or the development of US in megapolises and cities [5, 18].

The underground space should be analyzed as a multi-component system in which rocks or soils (the first component) are considered as a host medium for underground water (the second component), which are characterized by the variability of the hydrodynamic regime, complex chemical composition, variability of physical-chemical and bio-chemical conditions in the process of underground mining and operation of underground structures. It is necessary to take into account the presence and active functioning of underground microorganisms (the third component), which should be considered from the point of view of its influence on rocks, underground waters, and structural materials as well. The fourth component of US includes gases of various genesis – biochemical (the product of the activity of microorganisms, primarily in an anaerobic environment), and also deep and catalytic ones. The fifth component of the system, which is affected by all the US components, should be attributed to the support of underground mine workings. The justification for the choice of barring in the practice of mining operations is usually made depending on the degree of rocks disintegration,

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their ability to develop massive deformation and the formation of gravitational processes, the type and size of the mine working, its depth and orientation in space, and also the service life.

In the practice of designing and operating underground workings, due attention is usually not paid to the aggressivity of the impact of underground water and gases of various origins, and the activity of underground microorganisms in relation to the support materials is completely ignored.

Issues of mining operations safety in the 21st century at the Saint Petersburg Mining University were dealt with by: A.N.Shabarov, Yu.I.Kutepov, N.A.Kutepova, V.L.Trushko, V.P.Zubov, A.G.Protosenya, and others, including problems of underground mine workings stability at great depths, optimization of development systems to increase reliability when creating projects for the exploitation of new deposits [17, 34, 35], geodynamic monitoring [19], consequences of mine workings excavation in flooded rock masses with the threat of underground water breaks [20, 21].

Methodology. The Yakovlevsky mine of the Belgorod group of KMA deposits is an example of an object where the approach to US as a multicomponent system in the mining industry has been used and has successfully proven itself [10, 13, 15]. For 17 years, the prediction and management of dangerous mining and geological processes was carried out on the basis of the analysis of the multicomponent nature of the underground environment, while the influence of underground waters and the specifics of their chemical and biochemical composition, and also the physico-chemical conditions of the water environment were of fundamental importance in assessing the mining operations safety [11, 28]. The redox potential Eh, mV, and acid-base pH conditions of aquifers were determined directly in underground workings. The study of the microbiology and biochemistry of groundwaters was carried out for three main aquifers, which allowed to assess the negative impact of the microbiota on the light concrete stowing of the developed space, and also the reasons for the premature destruction of various types of barring, including arch supports. The Yakovlevskiy mine for the first time the negative impact of biochemical gases, such as carbon dioxide and hydrogen sulfide (the product of the vital activity of sulfate-reducing bacteria) was determined, as well as the impact of deep gas – radon, which contributed to the activation of microbial activity and, accordingly, biocorrosive processes. The nature of the barring materials destruction under the influence of a rich biocenosis with the participation of iron-reducing bacteria was studied using scanning electron microscopy (SEM) methods (Fig.1).

The combination of research methods (SEM and X-ray phase analysis XPA) allowed to determine the nature of metal barring corrosion by the formation of new ferruginous minerals: lepidocrocite (FeOOH) and goethite (α-FeOOH) under the influence of a rich biocenosis in underground waters [4]. The formation of iron oxohydrooxides significantly accelerates the corrosion processes, and the increase in volume causes stress strain state in the corrosion layers on the metal, which leads to cracks and other damage. The main destruction of the arch support is caused by iron-reducing bacteria due to the iron recovery $Fe0 \rightarrow Fe^{2+}$ and its subsequent removal, which significantly weakens the metal structure and causes plastic deformations of the support under the impact of relatively low rock pressure.Using the experience of assessing the US as a multicomponent system at the Yakovlevskiy mine makes it possible to perform on the same basis the prediction of mining and geological processes in the underground workings of the Kupol deposit (Fig.2), which is developed in the massive of sub-permafrost soils and is confined to the zone of the Okhotsk-Chukotka volcanic belt (OCHVP). We note

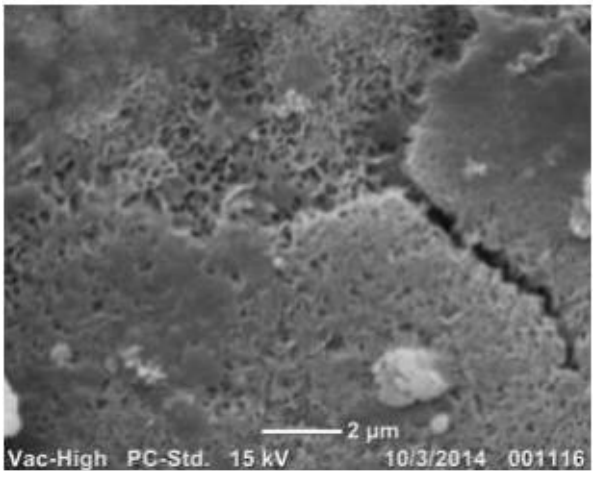


Fig.1. Corroded metal surface (photo by D.Yu.Vlasov)

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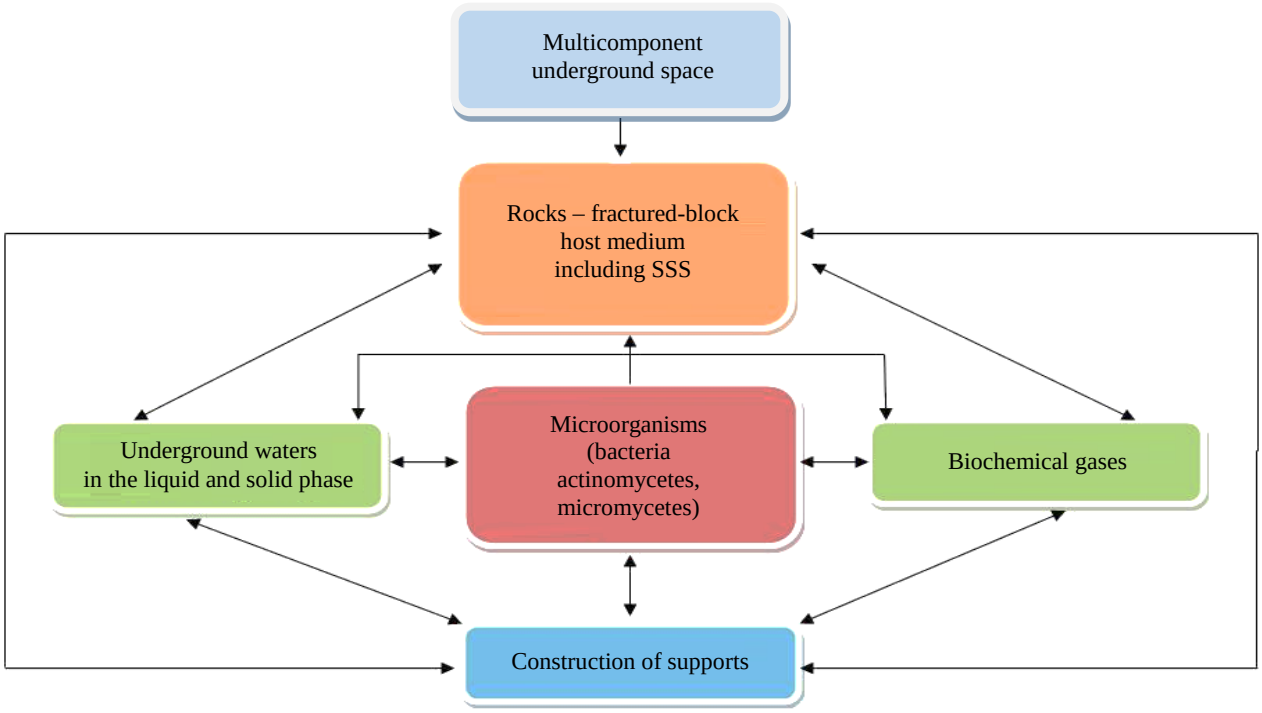


Fig.2. The interaction of the US components and the safety of mining operations

the need to use modern strategies in technological innovations in the mining sector of the economy [22]. The Kupol gold and silver deposit is being developed by the Russian enterprise Chukotka Mining and Geological Company, which is part of the Canadian Kinross Gold Corporation group.

Discussion. In the cut of the deposit, a complex of sedimentary, volcanogenic-sedimentary, volcanogenic and effusive rocks of the Upper Cretaceous system (K_2^2-K_2^3) is traced. They are represented by lavas of fluidic aphyric rhyolites of yellowish-gray color and their tuffs with a clear predominance of the latter, which lie according to the underlying middle thickness of the Upper Cretaceous. The strata composition is dominated by tuffs, clastolaves and lavas of rhyolites and trachyriolites, less often-ignimbrites of rhyolite composition, andesites, dacites and their tuffs. The study of the petrographic composition of ores in this region is reflected in the following works [1, 2, 7, 8, 23].

The Kupol deposit is located at the junction of the Sredne-Kayermraveemskiy fault of the north-south strike with the Krestovsko-Salamikhinskiy fault of the 1st deep-lying order (Fig.3) [9, 16, 26]. Rocks along the entire depth of the development are classified as intensely fractured according to the engineering-geological classification: the fracturing modulus according to the results of drilling reaches 6-10 cracks per 1 m, the distances between the cracks are 0.1-0.65 m [14]. The category of rock fracturing using the A_1 acoustic index at the Kupol deposit was not determined.

According to the results of previous studies of the host rocks, tubular friction anchors with a metal mesh were proposed as the main type of barring at the mine, and in areas subject to intensive fallout: shotcrete, polymer mixtures or cable-anchors. The danger of gravitational processes (landslides, collapses, etc.) is aggravated by the production of drilling and blasting operations during mining works. The formation of fallouts most often occurs at the contacts of tectonic faults cracks, which were recorded during specialized surveys in underground workings: the most dangerous areas are those with a large-block structure of the rock mass, usually confined to fault zones (Fig.4).

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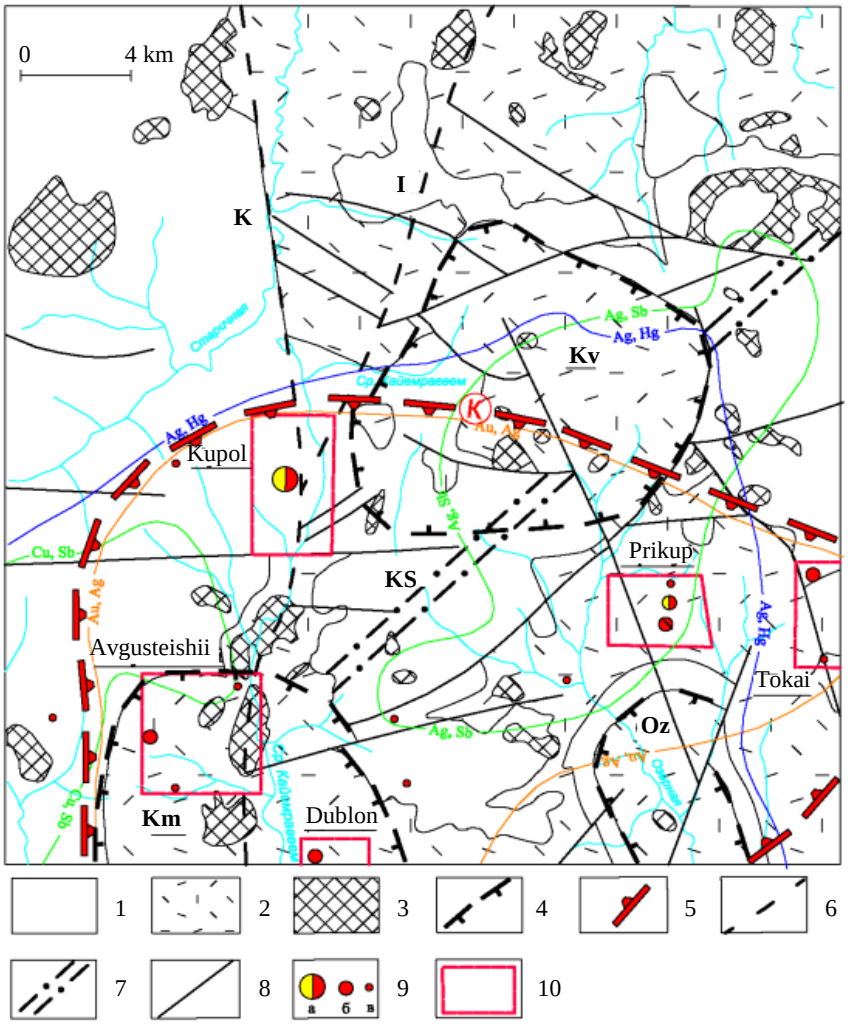


Fig.3 Structural and metallogenic scheme of the Kupol ore cluster [9]

1 – lavas and tuffs of andesites and andesibasalts of the middle thickness of the Upper Cretaceous; 2 – ignimbrites, tuffs, and lavas of Upper Cretaceous rhyolite; 3 – intrusive and subvolcanic bodies of various compositions; 4 – paleocalder boundaries (Kv – Kovalenkovskaya, Oz – Ozerninskaya, Km – Kayemraveyemskaya); 5 – contour of the Kupol ore cluster (K); 6 – axial zones of regional faults (K – Sredne-Kayemraveyemskiy, I – Imraveyemskiy); 7 – axial zone of the Krestovsko-Slamikhinskiy transregional deep fault (KS); 8 – other disturbances; 9 – deposits (*a*), ore occurrences (*b*) and the points of mineralization (*c*) of gold and silver; 10 – contours of prospective sites



Fig.4. Fallout in the stoping area of the Southern zone of the Kupol deposit, horizon +290 m (photo by I.S.Romanov 23.03.2020)

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Fig.5. Water occurrence from technological wells of anchor barring in the Northern zone of the deposit at the horizon of +200 m, the formation of iron hydroxides is visible (photo by I.S.Romanov 30.02.2020)

According to the results of the hydrogeological survey conducted in 2014 in the mine workings, at the horizon of + 440 m (depth of 68 m) in the massive of the frozen rocks, the presence of cryopegs with a chloride-sulfate, calcium-magnesium composition, an abnormal mineralization of 445.27 g/dm^3, and very low pH values of 1.96 was established. In the zone of influence of cryopegs with high acidity, intense corrosion of metal structures – anchors and mesh – was observed, which caused the collapse of the workings for 40-50 m. The destroyed anchors were a "pale" of ochre-colored fraction. The same colors were noted for the torn wire mesh. The presence of cryopegs was established in Yakutia, in the tundra zone of the Kolyma Lowland on the East Siberian Sea coast, etc. [3, 24, 27].

Currently, the main front of mining development is concentrated below the zone of sub-permafrost rocks, where there is an active manifestation of sub-permafrost waters with a temperature of 1-2 °C and a mineralization of 3-5 g/ dm^3 [12] (Fig.5).

In most cases, the intensive flow of sub-permafrost water into the mine is associated with the nature of rock fracturing – the degree of crack opening, their length, the presence of aggregate, etc. As examples, we can cite the results of water occurrences observations: crack-pore permeability is characteristic of ash tuffs of andesites, the outflow of water from them occurs through poorly opened cracks; crack permeability is characteristic of dense rock masses with weak fracturing-rhyolites, basalts, andesites; crack-vein permeability is characteristic of tuffs of different composition with a high degree of fracturing – concentrated outflow of water occurs through gaping open cracks. Forecasting of breakthroughs of sub-permafrost water in mine workings is practically not carried out, although at the stage of research it was established that the sub-permafrost horizon belongs to the pressure horizon, the upper water barrier of which is a thick layer of sub-permafrost, reaching 250-300 m at the Kupol deposit.

Currently, the main part of the preparatory and stoping works is located below the bottom of the sub-permafrost and, accordingly, the widespread manifestation of sub-permafrost waters should be assessed from the point of view of their level of danger and the probability of underground mine workings flooding: due to the high water content of the face, at the rate of the face advance set by the technical regulations for a cycle of 4.2 m, this indicator is halved. This indicator is achieved by using modern means of mechanization: drilling of blast holes is carried out by a self-propelled drilling rig (SDR) SandvikDD 420-40C with a drill rod length of 4915 mm; charging of blast wells in a mechanized way using an Anfo42-01R pneumatic loader mounted on a self-propelled chassis and equipped with a hydraulic lift. Granular explosives based on ammonium nitrate are used as the explosive mass; cleaning of the exploded rock mass is carried out by a CAT-1700 loading and delivery machine with a shovel volume of 6.6 m^3; barring of the mine workings is implemented by the SDR for the installation of anchor supports SandvikDS 410-C, SandvikDS 411-C. The SDR is equipped with an arrow with a drilling module for drilling holes and installing friction anchors, and an arrow for grabbing and installing a welded mesh. The value of the face advance per cycle in the amount of 4.2 m at the company was determined on the basis of technical and economic indicators, taking into account the minimum cost of 1 m of mining excavation and the productivity of mining equipment. When using the above-mentioned means of mechanization, the full cycle of tunneling operations at the field takes

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two shifts of 11 hours, which is the most optimal option for the company. In addition, it is necessary to take into account the corrosion ability of underground water in relation to the barring materials – metals (tubular friction anchors, metal mesh and cable-anchors), shotcrete and polymer concrete. The corrosion capacity of underground water in mine workings should be analyzed according to the following items:

• redox and acid-base conditions in terms of Eh, mV (redox potential) and pH, which must be measured *in situ* using selective electrodes;

• chemical composition of underground waters according to the expanded list, including indicators of the content of easily oxidizable organic matter (permanganate oxidability) and the total amount of organic components-chemical oxygen demand (COD), which determine the value of Eh, mV;

• microbiological and biochemical specificity of groundwater, which is estimated by the value of BOD_5 (biological oxygen demand for 5 days), and also by sowing on selective media and gene-molecular analysis.

Such studies were performed for the first time for the Kupol deposit conditions (Table 1).

Table 1

Chemical composition of underground waters of the sub-permafrost aquifer

Determined indicators	Results of the study	Regulatory documents
Sodium, mg/dm^3	318	FR.1.31.2011.10615
Potassium, mg/dm^3	7.2	FR.1.31.2011.10615
Calcium, mg/dm^3	336	FR.1.31.2011.10615
Magnesium, mg/dm^3	137	FR.1.31.2011.10615
Ammonium ion, mg/dm^3	0.11	PND F 14.1:2:4.262-10
Total Ferrum, mg/dm^3	0/40	FR.1.31.2011.10615
Hydrocarbonate-ion, mg/dm^3	169	GOST 31957-2012
Chloride-ion, mg/dm^3	85	PND F 14.1:2:3.96-97
Hydrogen sulfide, mg/dm^3	< 0.002	PND F 14.1:2:4.178-02
Sulfate-ion, mg/dm^3	1770	PND F 14.1:2.159-2000
Nitrate-ion, mg/dm^3	< 0.1	PND F 14.1:2:4.4-95
Silicic acid (Si), mg/dm^3	< 0.05	NDP 10.1:2:3.100-08
COD, mgO_2/dm^3	14	PND F 14.1:2:3.100-97
Permanganate oxidability, mgO_2/dm^3	2.6	PND F 14.1:2:4.154-99
BOD_5, mgO_2/dm	2.3	PND F 14.1:2:3.123-97
Hydrogen index (field measurements), pH unit	7.2 (7.0)	PND F 14.1:2:3.121-97
Dry residue, mg/dm^3	2770	PND F 14.1:2:3.261-10
Total water hardness, ^{0}H	28	GOST 31954-2012
Carbon dioxide free, mg/dm^3	11	FR.1.31.2005.01580
Petroleum products, mg/dm^3	0.017	PND F 14.1:2:4.128-98

Note. Chemical analysis of the water was performed in the laboratory of LLC "Center for Ecoanalytic Services "Opyt" on 03.06.2020.

The high content of sulfates in water is associated with the oxidation of sulfides (the main minerals that contain gold and silver in paragenesis), the presence of thionic bacteria that produce sulfuric acid, and biochemical hydrogen sulfide. In addition, alkaline (Na^+) and alkaline-earth elements (Ca^{2+} and Mg^{2+}) are present in groundwater, and the latter determine its high hardness, reaching 28 °H. However, the pH value indicates a neutral environment, which is caused by the acidification of water due to the sulfate component and the biochemical processes of H_2S generation.

The sub-permafrost aquifer belongs to the water systems with active microbial activity in the Kupol and Mayskoye deposits, which is proved by microbiological studies carried out in 2019-2020 at St. Petersburg State University under the supervision and direct participation of Professor D.Yu.Vlasov. It should be emphasized that the redox conditions in the sub-permafrost water horizon with difficult water exchange due to the presence of a regional water barrier-the thickness of sub-permafrost rocks are usually characterized by negative Eh values. The underground water at the Yakovlevskiy deposit had an Eh value of –78÷–85 mV, measured at a horizon of – 425 m. Oxygen-free conditions in aquifers determine the presence of heterotrophic anaerobic microorganisms – sulfate-

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reducing bacteria and iron-reducing ones. It is important that iron bacteria belong to psychrophilic groups of microorganisms that develop well at 4 °C and lower temperatures [29]. As is known, sulfate-reducing bacteria (mesophilic forms of microorganisms) generate the formation of hydrogen sulfide and are considered as tolerant to low temperatures.

The study of the third component – the underground microbiota at the mine was initiated due to the fact that the features of the development of metal supports corrosion at the Kupol deposit are similar to the nature of their destruction at the Yakovlevskiy KMA deposit, where the biocorrosion nature of the supports destruction and concrete stowing was established. The same research was carried out at the Mayskoye deposit, located 300 km from the Kupol deposit. Samples of underground water, materials of the destroyed metal barring, wooden rubble work and clay gouge were taken. The sample at the Kupol and Mayskoye deposits was taken with mandatory compliance with the rules of sterility. Determination of groups, species, genera, and the number of microorganisms was carried out by sowing on nutrient liquid and solid media, and microscopic studies.

As a result of the analysis, micromycetes, bacteria and actinomycetes were identified. The dominant genus of micromycetes in underground water is *Aspergillus*, and in samples of destroyed support materials – *Penicillium, Aspergillus, Trichoderma, Cladosporium,* which play a significant role in the destruction of barring materials. Among the identified micromycetes, the predominate species were the ones introduced by humans into the mine space, and also come with a flow of ventilation air. Species of the genus *Penicillium*, capable of developing at low temperatures, could be in the sub-permafrost and adapt to the conditions of the frozen thickness. This genus can be attributed to psychrophiles.

Bacteriological analysis revealed the presence of a wide range of bacteria. The number of aerobic organotrophic bacteria varies between $1 \cdot 10^3 – 1 \cdot 10^7$ CFU in 1 ml of water or 1 g of rock. The group of psychrophilic microorganisms is mainly represented by iron-bacteria, iron-reducing and iron-oxidizing, and also mesophilic groups that have shown tolerance to low temperatures. Among the bacteria, the predominant morphotypes were mucoid colonies of various colors, which most often belong to iron-oxidizing forms. In the samples of metal structures, the presence of thionic bacteria was also noted, which generate sulfuric acid and cause metal corrosion in an aerobic environment. As nutrients, psychrophiles use cold-adapted ferments (proteins), which gives them an additional substrate for growth and development, and at lower temperatures – to maintain life.

The first studies of microorganisms that were found in sub-permafrost rocks and in fossil ice were initiated by the famous Russian microbiologists V.M.Omelyanskiy in Yakutia and B.L.Isachenko in the Far East in 1911 and 1912, respectively. A large amount of microbiological research was carried out at polar stations in Antarctica by American and Russian researchers in the 70s-90s of the 20th century. The performed experimental work (1985-1993) by D.G.Zvyagintsev, D.A.Gilichinsky, G.M.Khlebnikova, and others showed that in the frozen thickness of rocks with a temperature of –12 °C, up to 10^8 cells of microorganisms can be contained in 1 g. The selected microorganisms mostly belonged to psychrophilic groups, 95 % of these cells did not grow at temperatures above 30 °C, among them were separated sulfate-reducing and methanogenerating bacteria, anaerobic actinomycetes.

In the 21st century microbiological studies in sub-permafrost profiles have expanded significantly. According to the results of research by the Institutes of the Russian Academy of Sciences, Lomonosov Moscow State University in the Arctic, the tundra zone of the Kolyma Lowland off the coast of the East Siberian Sea, in the water-saturated horizons of the Varandey Peninsula, in the area of the Yakutskoye lake in the Kolyma Lowland various forms of microorganisms (from units to hundreds of thousands of CFU in 1 g of air-dry soil or 1 ml of mineralized water) have been identified [6, 25, 31-33]. Currently, the activity of aboriginal forms of microorganisms (in the massive of frozen rocks, in cryopegs and sub-permafrost waters), as well as introduced microorganisms, should be studied in mine workings. The activity of microorganisms should be considered, first of all, from the point of view of the biocorrosion processes development in the barring of support structural materials.

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The fourth component, gases, was initially detected during the sampling of sub-permafrost waters by the characteristic smell of hydrogen sulfide, which was confirmed by laboratory studies. The low value of hydrogen sulfide (H_2S) in the sample is associated with a high rate of oxidation of this gas, which is accompanied by an increase in the content of the SO_4^{2-} ion. The presence of hydrogen sulfide is an indicator of the anaerobic environment presence in the sub-permafrost water. The product of the respiration of microorganisms is carbon dioxide (CO_2), the value of which reached 300 mg/dm^3 in the conditions of the Yakovlevskiy deposit. These gases are aggressive to structural materials – CO_2 to concrete, H_2S to metals and concrete.

As noted earlier, active corrosion of the structural elements of the metal barring is observed in the places where the sub-permafrost waters are discharged. It is necessary to take into account the anaerobic conditions in underground waters, which implies the existence of electrochemical processes, the development of which leads to the thinning of metal structures due to the reduction of iron $Fe^0 \rightarrow Fe^{2+}$. The high content of sulfate ion suggests the possibility of sulfate corrosion in concrete, accompanied by the formation of calcium hydrosulfoaluminate ($3CaO \cdot Al_2O_3 \times \times 3CaSO_4 \cdot 3lH_2O$). It is known that the generation of this cement-like mineral in the form of crystallohydrates contributes to a significant increase in the volume of the material due to the crystallization pressure of more than 10 MPa, which leads to the disintegration of concrete.



Fig.6. Corrosion of metal plates of the Northern section of the Kupol deposit, horizon +400 m (photo by I.S.Romanov 05.12.2019)

At the Kupol deposit, the main type of barring the fractured rocks is tubular friction anchors paired with a metal mesh. During the visual inspection of the barring, it was noted that the support is subject to active corrosion in all areas (Fig.6). This fact led to a more detailed analysis of the corrosion genesis and its development: the company is supplied with new supports, and corrosion develops in just a few days. The performed observations indicate the activity of biocorrosion. (Fig.7). Part of the material of the new anchor support was stored in the immediate vicinity of the tunneling face. The photos show the point corrosion manifestations caused by the drip of sub-permafrost water for 4 hours. The formation of a mucoid plaque on the metal is caused by the activity of the iron-oxidizing bacterium *Gallionella ferruginea*. In addition to corrosion of the metal barring, there is also biocorrosion of shotcrete [30].



Fig.7. Manifestation of biocorrosion on new tubular friction anchors (photo by I.S.Romanov 15.03.2020)

The rate of biocorrosion development is usually an order of magnitude higher than chemical corrosion, which in the absence of specialized monitoring can lead to the formation of large-volume fallouts.

Based on the analysis of the underground space as a multicomponent environment, the forecasting and systematization of mining and geological processes at the Kupol deposit was carried out, observations and control of which should be included in the system of integrated monitoring at the

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operating mining company in complex engineering and geological conditions, which will contribute to improving the safety of mining operations.

The systematization of mining and geological processes was carried out for two zones: the first – within the horizon of +525 m - +300-250 m, the zone of sub-permafrost; the second – the horizon of +300 m - +250 m below the sub-permafrost bedding. The systematization is carried out according to seven parameters (Table 2).

Results. The forecasting of dangerous mining and geological processes at the Kupol deposit was carried out on the basis of the analysis of US as a multicomponent system: rocks, underground waters, microbiota, gases and structural materials of supports, which are closely related to each other. A change in one of the components leads to a disruption in the operation of the entire system, reducing the level of safe operation of the deposit. The features of the Kupol deposit location in the node of tectonic faults determined its formation in the conditions of active tectonic activity and hydrothermal processes in the Upper Cretaceous, the specifics of the ore body structure and the high degree of disintegration of various petrographic types of host rocks. Complex mining and geological conditions dictate the need to use tubular friction anchors paired with a metal mesh as the main barring, and in particularly difficult areas, additional cable anchors and (or) shotcrete or polymer concrete.

The deposit is located in the zone of sub-permafrost development with a capacity of 250-300 m. Cryopegs with abnormally high mineralization and extremely low pH were found in the sub-permafrost at +440 m. The impact of cryopegs on the metal support led to its rapid destruction and the fallout formation in the roof. The sub-permafrost aquifer is characterized by a pressure-free flow regime and can be attributed to water systems with difficult water exchange, which implies the presence of a reducing (oxygen-free) environment with the value of the redox potential Eh < 0 (by analogy with the aquifers of the Yakovlevskiy KMA deposit). Underground waters of chloride-sulfate sodium-calcium, brackish with a mineralization of 3-5 g/dm^3 have a high hardness due to the presence of alkaline-earth elements, but a neutral water reaction.

It is experimentally proved that underground waters serve as the main source of microorganisms, among which micromycetes and iron bacteria were isolated, while the latter belong to psychrophiles. Among the iron bacteria, aerobic forms of iron-oxidizing and anaerobic (iron-reducing) are established, which is of fundamental importance when considering the corrosion of metal supports. The presence of mesophilic forms of microorganisms – sulfate-reducing (anaerobic) and thionic (aerobic), which are considered as tolerant to low temperatures in the underground environment, has been recorded. Microbiological studies carried out in cryopegs and frozen soils in the 20th and 21st centuries by institutes of the Russian Academy of Sciences, Moscow State University, etc., confirm the presence of various physiological groups of microorganisms, not only psychrophilic forms, but also mesophiles, that develop steadily at low temperatures.

The activity of sulfate-reducing bacteria is accompanied by the generation of hydrogen sulfide, which is established by a distinct smell when unloading sub-permafrost water into mining workings. As is known, this gas is easily oxidized, however, its presence was recorded in the analysis of the chemical composition of sub-permafrost waters. The activity of microorganisms is also accompanied by the formation of CO_2, which is considered as a product of their respiration. The presence of H_2S is dangerous for concrete and metals, given that this easily soluble gas leads to a decrease in pH below 4.

The corrosion processes of the supports must be considered as dangerous. According to the performed studies, by their nature, they can be divided into chemical corrosion, which includes sulfate and carbon dioxide, biocorosis and electrochemical. The most dangerous is biocorrosion, the rate of which is an order of magnitude higher than chemical corrosion. This type of corrosion occurs due to the metabolites of microorganisms-acids, gases, and also ferments (enzymes) and the direct activity of the cells of the microbiota that form biofilms on the surface of the supports. It is also necessary to analyze the high probability of electrochemical processes of steel that lead to ionization of metal atoms ($Fe^0 \rightarrow Fe^{2+}$) under reducing conditions and thinning of support structures.

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Table 2

Systematization of mining and geological processes in the underground workings of the Kupol deposit within the sub-permafrost zone and beyond it

The genetic type of the process	Danger level	Name of the process	The main factors determining the development of the process	Scale of manifestation	Development in time	Negative consequences of the process
1	2	3	4	5	6	7
Zone below the bedding of sub-permafrost rocks (below the horizon +300 m -+250 m)						
Endogenous (natural)	High	Excessive tectonic stresses	Structural and tectonic features of the area in the zone of alpine folding and active new movements	On all horizons below the absolute mark of +250 m in the sub-permafrost massive	Constant	The possibility of developing rock bursts in the least fractured rocks, the destruction of supports in the condition of performing calculations without taking into account excessive stresses, deformation of the sides of workings, "spalling" of rocks
Exogenous (natural-technogenic)	High	Gravitational processes in the roof and sides of workings: collapses, fallouts of various volumes	Features of the geological structure: weakened areas of tuffs and cutting dikes in tectonic fault zones	Widespread in the ore body	Hours	Disturbance of the roofstability, stability of mining operations, increased risk of injuries, material costs for the elimination of consequences
				Local in the host rocks	Hours, days	
		Formation of local domes in andesites	Intense tectonic fracturing and destruction of the anchor support	Local	Days, weeks	
		Water appearance of sub-permafrost waters	Discharge of the pressure aquifer in active fracturing zones	Local flooding of workings	Constant	Negative impact on the speed of mining operations
		Development of sulphate aggressiveness of sub-permafrost waters in relation to concrete	High values of the sulfate ions content in sub-permafrost waters	Local, in zones of sub-permafrost waters discharge	Days, weeks	Intensification of gravitational processes in the collapseareas
		Corrosion of metal supports	The presence of micromycetes and psychrophilic groups of bacteria, including iron-oxidizing and iron-reducing species, and also sulfate-reducing	Local	Months, years	Pre-early work off support and its destruction in progress
		Corrosion of shotcrete	Sulfate aggressiveness of groundwater and biocorrosive processes in the activity of sulfate-reducing bacteria	Local	Months	Pre-early destruction of shotcrete
		Biochemical aggressiveness of sub-permafrost waters	Chemical composition of waters as a source of nutrient and energy substrates for the development of microorganisms	Wide spread in underground waters	Constant	Active development of construction materials biocorrosion in mining operations in water-bearing zones

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End of Table 2

The genetic type of the process	Danger level	Name of the process	The main factors determining the development of the process	Scale of manifestation	Development in time	Negative consequences of the process
1	2	3	4	5	6	7
Sub-permafrost zone (above the horizon +300 m - +250 m)						
Exogenous (natural-technogenic)	High and very high	Presence of local cryopegs with abnormal mineralization and low pH < 2	Selected areas in the sub-permafrost zone	Local	Day	Complete destruction of the barring in a short time and the roofcollapse
	Middle and low	Fallouts	Disintegration of ore bodies in the nodes of tectonic faults under intense rocksfracturing	Local	Hours	Local disturbance of theface stability and roof of the workings
		Deformations ofroof subsidence and sides of workings during stoping operations	Violation of the technology of the stowing works mode: the delay of the stowing from the speed of conducting stoping works	Local	1-7 days	Local displacement of rock blocks in the roof and sides of workings
		Increased disintegration (fracturing) of rocks in the roof and sides of workings	Conducting drilling and blasting mining operations	Narrow-local	Hours	Intensification of rock fallouts in the roof and sides of mine workings
		Thawing of sub-permafrost	The supply of warm air during the ventilation of workings in the summer	Local	End of June, July, beginning of August	Reduction of the strength of the fractured rock thickness in the roof and sides of the workings
		Corrosion of anchor support and metal mesh	Impact of psychrophilic forms of microorganisms	On all horizons	Months, years	The probability of formation of large volume fallouts
		Corrosion of shotcrete	Impact of psychrophilic forms of microorganisms	On all horizons	Months, years	Intensification of the rock weathering processes in the roof and sides of workings, the probability of dangerous gravitational processes

The analysis and systematization of dangerous mining and geological processes at the Kupol deposit can be used as a basis for the formation and development of integrated specialized monitoring as a control and monitoring tool, while it becomes possible to manage the safety of mining operations, the complexity of which will only grow as the depth of development increases in the sub-permafrost layer with a high degree of flooding of workings and the corrosive ability of underground water.

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