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R. E. DASHKO[1], *Professor at the Hydrogeology and Engineering Geology Department, Doctor of Geological and Mineralogical Sciences, regda2002@mail.ru*
I. S. ROMANOV[1], *Post-Graduate Student*

[1] *Saint-Petersburg Mining University, Saint-Petersburg, Russia*

SAFETY OF MINING IN THE KUPOL DEPOSIT BASED ON THE ANALYSIS AND EVALUATION OF GEOLOGICAL PROCESSES IN UNDERGROUND MINE (CHAO, ANADYR DISTRICT)

The adversities of geology and permafrost hydrogeology in operating roadways under conditions of increasing depth of mining in the Kupol deposit are formulated. It is emphasized that safety of mining will depend on endogenous and exogenous processes. The article presents the systematization of geological processes by the criterion of their hazard for two zones of the Kupol deposit: the upper zone of permafrost rocks and the lower zone of thawed rocks. The importance of taking into account the biocorrosion processes induced by the activity of various microorganisms—cryophiles, mesophilic micromycetes tolerant to low temperatures and some anaerobic bacteria—is for the first time highlighted. The geological processes systematization for the Kupol deposit has been accomplished for the first time ever.

Keywords: *gold-and-silver deposit, underground mine, permafrost rock, jointing, groundwater, geological processes, microorganisms, biocorrosion, mine support systems, operational safety*

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General information

The Kupol deposit discovered in 1995 is now a mining project of Canada's Kinross Gold Corporation. This is a shallow epithermal deposit within the Okhotsk–Chukotka Volcanic Belt (OCVB). The mineralization depth of such type deposits ranges from 300 to 1500 m, the extension is more than 300 km and their width is 100–300 m (**Fig. 1**) [1]. Mineralization of the Kupol deposit took place in the Upper Cretaceous age and was connected with the hydrothermal processes [2].

The close spacing between the deposit and the Middle Kaiemraveem and Imraveem faults governs essential disintegration of the strata. The geological section contains traceable sedimentary-volcanic, volcanic and effusive formations of the Lower and Upper Cretaceous age. The permafrost thickness of the Kupol deposit ranges from 250 to 300 m.

Extraction of mineral reserves from the deposit is carried out under the permafrost floor. The mine uses two mining systems: cut-and-fill and sublevel stoping with complete backfilling. At the moment, the latter mining system is used in the mine [3].

Mining safety factors

The matters of principle in the mining safety evaluation and geological prediction at the Kupol deposit include:

- the stress–strain behavior of rocks mass, governed by the mining depth and excessive tectonic stresses in the zones of the Alpine folded belt;
- the features and specificity of jointing of ore and enclosing rock mass with regard to the in-depth variation in the thermodynamic conditions due to the presence or absence of ice cementation;
- the aquifers with their water abundance connected with rock mass jointing, lithological composition of filler and with the hydrodynamics of the water-bearing strata—either free or confined groundwater flow, which govern water inflows and possible groundwater inrushes;
- the chemical and biochemical composition of permafrost and subpermafrost water, which conditions aggressivity of water relative to mine support materials: steel, concrete, polymers;
- the impact of microorganisms on the support material, which is usually neglected in mine projects;
- the free gases of the hypogene, catalytical and/or biochemical genesis in rock mass and groundwater;
- the alteration of mine support systems with time under the integrated impact of groundwater, gases and microorganisms.

The excessive tectonic stresses take an important place in the geological analysis. The in-situ measurements at the depths down to 250–300 m detect no tectonic stresses. The excessive stress assessment beneath permafrost reveals high concentration ratios of 1.8–2.2 of horizontal stresses ($\sigma 2 \neq \sigma 3$) as against vertical stress ($\sigma 1$). The same absence of the tectonic stresses in permafrost and their absence in thawed rock mass was observed in the Irokinda deposit [4]. The present authors think, ice-bearing permafrost experiences plastic deformation which avoids stress concentration. It is known that under small pressure difference, ice is capable to plastic yielding. Thus, it is only possible to determine, exactly and reliably, the excessive stresses in the subpermafrost rock mass which is free from cementing ice.

Jointing of rocks can be assumed to be tectonic and nontectonic. High jointing (absolute value of jointing by drilling data is 6–10 joints per 1 m, spacing of joints is 0.1–0.65 m) conditions the choice of the standard mine support system of friction bolts with steel reinforcing mesh, which is sometimes added with shotcrete or polymeric lining or cable bolts.

Groundwater and microbial impact on mining safety

The impact of groundwater on mining safety lacks attention, particularly, this relates chemical and biochemical composition of groundwater. The ample research of

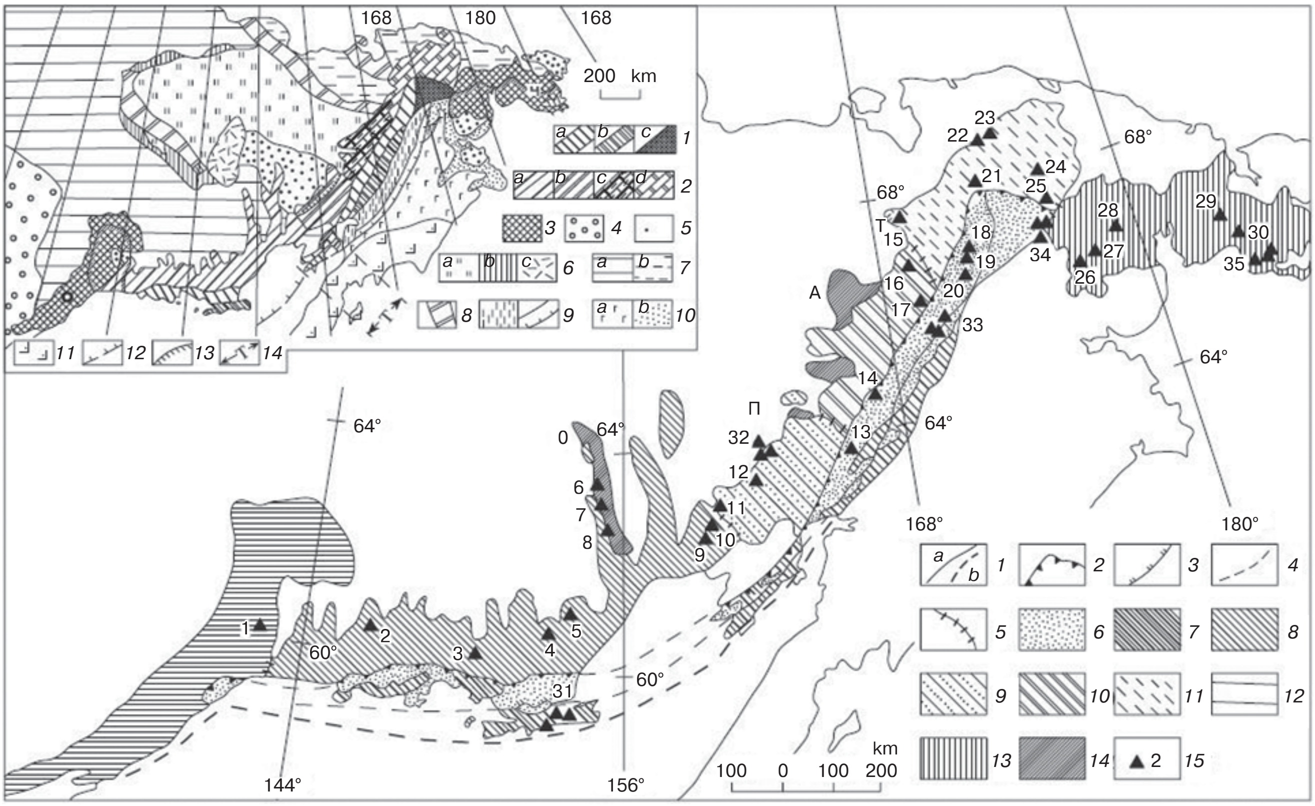

Fig. 1. Zoning of OCVB and layout chart of gold-and-silver deposits [2]:

1—generalized limits of magmatic deposits in OCVB: Albian–Santonian (a—on land, b—in aquatic area); 2—boundary of internal and external zones of OCVB; 3—boundaries of sub-zones of fault troughs and magmagenetic swells (dashes are oriented toward sub-zone of fault troughs; 4—extension of boundaries 2 and 3 in aquatic area); 5—boundaries of sectors in external zone and in side zones; 6—volcanos in internal zones; 7—magmagenetic swells in OCVB with discovered formations of Taigonos Volcanic Arc: Upper Paleozoic–Lower Albian age; 8–11—external zone of OCVB (sectors: 8—Okhotsk, 9—Penzhin, 10—Anadyr, 11—Central Chukotka); 12 and 13—side zones (12—Western Okhotsk; 13—Eastern Chukotka); 14—late orogenic (late Barremian–early Albian) Mesozoic structures (O—Omsukchan graben, and downwarpings: UP—Upper Penzhin, U—Umkuveem, A—Ainakhkurgen, T—Tytylveem); 15—gold-and-silver deposits (1—Khakandzha, 2—Burgaglykan, 3—Karamken, 4—Nyavlenga, 5—Juliet, 6—Arylakh, 7—Lunnoe, 8—Dukat; 9—Quartz bald peak, 10—Irbychan, 11—Oroch, 12—Kegali, 13—Sergeevskoe, 14—Irguveem, 15—Dvoinoe, 16—Kupol, 17—Gornostai, 18—Envymaam, 19—Arykvaam, 20—Kaienmyvaam, 21–Kytlatap, 22—Promezhutochnyi, 23—Ruda ore peak, 24—Televeem, 25—Proval lakes, 26—Zhilnoe, 27—Valun, 28–Terkgei, 29—Korrida, 30–Pepenveem, 31–35—copper-and-porphyry deposits: 31—Koni-Pyagina group, 32—Erguveem group, 33—Olkhovka group, 34—Tanyurer group, 35—Providenie group).

Insert: OCVB in the structure of Northeastern Russia: 1–3—OCVB: 1—internal zone (a—sub-zone of graben-synclines, b—sub-zone of magmagenetic swells, c—not specified by kind), 2—external zone (sectors: a—Okhotsk, b—Penzhin, c—Anadyr, d—Central Chukotka); 3—side zones (WO—Western Okhotsk, EC—Eastern Chukotka); 4—Siberian Platform; 5—Pre-Riphean betwixt rock mass (non-overlaid with OCVB volcanic rocks); 6 and 7—Verkhoyansk–Chukotka folded area: 6—Mesozoic structures: Alazeya–Oloi system (a—island-arc and oceanic terrains, b—marginal upheavals of Paleozoic carbonate platforms, c—Kolyma's Riphean upheaval), 7—Yana–Kolyma (a) and Chukotka (b) terrains of passive continental outskirts; 8—rift-type structures of the early orogenic development of Mesozoic formations; 9—Penzhin inter-arc downwarping (a) and Talovaya–Main nonvolcanic arc (b) of the Mesozoic island-arc system; 10—Anadyr–Koryak island-arc and oceanic terrains, Laramide structures: a—internal zone, b—external zone; 11—Olyutor–Kamchatka island-arc and oceanic terrains, Cenozoid structures; 12—Pre-Albian seismic focus zone; 13—presumptive betwixt rock masses overlaid by OCVB volcanic rocks; 14—Taigonos syntaxis.

groundwater microbiology and biochemistry was undertaken and accomplished in the Yakovlevo field of high-grade iron ore in the Kursk Magnetic Anomaly. The integrated study of groundwater in three aquifers revealed the adverse effect exerted by microbiota on backfill made of light aggregate concrete and exhibited the causes of premature failure of arch support. The studies dictated in-situ evaluation of Eh, mV (redox potential) for the correct identification of aerobic and anaerobic microorganisms, as well as feasibility of electrochemical processes. The indispensable characteristics of water chemistry are the easily oxidized organics composition (permanganative value), and the total organics content by the chemical oxygen demand (COD) and five-days biological oxygen demand (BOD_5). The contents of hydrogen sulfide, sulfates and ammonium should be measured in-situ [5–7].

Table 1. Chemistry of groundwater in subpermafrost aquifer*

Parameter	Value	Regulatory document
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
Ion ammonium, mg/dm^3	0.11	PND F 14.1:2:4.262-10
Total iron, mg/dm^3	0.40	FR.1.31.2011.10615
Ion bicarbonate, mg/dm^3	169	GOST 31957-2012
Ion chloride, 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
Ion sulfate, 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 (by Si), mg/dm^3	<0.05	NDP 10.1:2:3.100-08
COD, mg/dm^3	14	PND F 14.1:2:3.100-97
Permanganative value, mg/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
pH	7.2 (7.0)**	PND F 14.1:2:3.121-97
Solid residue, mg/dm^3	2770	PND F 14.1:2:3.261-10
Total hardness, ^{0}H	28	GOST 31954-2012
Free carbon dioxide, mg/dm^3	11	FR.1.31.2005.01580
Oil products, mg/dm^3	0.017	PND F 14.1:2:4.128-98

*Chemical analysis was carried out at a certified laboratory of OPYT Center for Ecoanalytical Services, Saint-Petersburg, dated 3 June 2020
**In-situ measured

Fig. 2. Corrosion of metal strips, Severny site, Kupol mine, level +400 m (5 December 2019 photo courtesy I. S. Romanov)

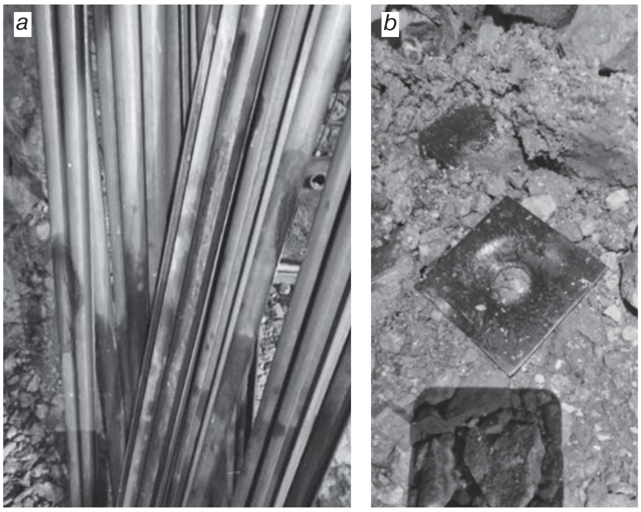

Fig. 3. Biocorrosion of new rock bolts:
a—steel tubes; *b*—collar (15 March 2020 photo courtesy of I. S. Romanov)

Subpermafrost groundwater was sampled in Kupol mine, on the level of +0 m, from seepages in jointed andesite rock mass. The extended chemical analysis data are compiled in Table 1.

Hydrogen sulfide (H_2S) in water was identified during the chemical analysis and by the smell when sampling. The low value of H_2S in the sample is connected with the high oxidation rate of the gas and with the increased content of ion SO_4^{2-}. The hydrogen sulfide presence points at the anaerobic medium in the subpermafrost aquifer which also represents the hindered water exchange environment conditioned by the thick permafrost cover. In this case, Eh can drop to –70 mV and below. The easily oxidized organics value and COD are essentially underestimated as the time span of 3–4 days between sampling and testing halves the permanganative value and, accordingly, COD. The value of BOD_5 is only reflective of aerobic microorganisms. At the same time, the reducing conditions predetermine vitality of anaerobic microorganisms, which is proved by the microbiological studies.

The extended chemical analysis of subpermafrost groundwater defines their aggressivity relative to steel structures and concrete. The reducing conditions in the subpermafrost aquifers assume the electrochemical processes of $Fe^0 \rightarrow Fe^{2+}$, which result in thinning of metal structures. The high content of ion sulfate initiates sulfate corrosion due to formation of calcium hydrosulfoaluminate ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 3lH_2O$) which promotes an essential increase in the material volume and in the crystallization pressure by more than 10 MPa, which induces disintegration of concrete [8, 9].

Subpermafrost groundwater are for the first time examined to find various microorganisms and are rated as the sources of microorganisms in mines. The same studies were implemented in May gold mine 300 km away of Kupol mine. The microbiological studies are implemented by Doctor of Biological Sciences, Professor of the Saint-Petersburg Mining University D. Yu. Vlasov. The microbiological analysis points at the domination of *Aspergillus* in groundwater and *Penicillium, Aspergillus, Trichoderma* and *Cladosporium* in the materials of mine support systems. These bacteria have an essential part in the support failure. The identified cryophilic bacteria represent mostly iron-reducing and iron-oxidizing microorganisms. These bacteria activate at *t* below 20 °C and are specifically active at $T = 4$ °C. In the Kupol deposit, sulfate-reducing and iron-reducing bacteria are mostly found. As known, sulfate-reducing bacteria promote origination of hydrogen sulfide and,

Table 2. Systematization of geological processes in Kupol mine

Geological processes inside and outside permafrost rock mass						
Genesis	**Hazard level**	**Name**	**Major influences**	**Scale**	**Time duration**	**Adverse consequences**
Under permafrost strata floor (beneath the depth of 300–250 m)						
Endogenous (natural)	High	Excessive tectonic stresses	Structural and tectonic specifics of the zone of the Alpine folding and modern active movement	On all levels below actual elevation of +250 m in subpermafrost strata		Possible rock bursts in weakly jointed rocks, failure of mine support (if mine support design disregards excessive stresses), deformation and spalling of sidewalls
Exogenous (natural-and-manmade)	High	Gravity-induced processes in roof and sidewalls of roadways: falls, inrushes of any volume	Geological structure features: softened areas in tuff and counter-dykes in tectonic faulting zones	Everywhere in ore body	Hours	Roof instability, destabilization of mining operation, elevated injury risk, raised expenses connected with accident aftereffect elimination
				Locally in enclosing rock mass	Hours and days	
		Local doming in andesite	Intense tectonic jointing and failure of rock bolt system	Local scale	Days and weeks	
		Ingresses of subpermafrost water	Relaxation of confined aquifer in the zones of active jointing	Local flooding of roadways	Permanently	Decelerated advance velocity of heading and stoping
		Sulfate aggressivity of subpermafrost water relative to concrete	High content of sulfate-ions in subpermafrost water	Locally in zones of relaxation in subpermafrost water	Days and weeks	Intensified gravity-induced processes in failure sites
		Mine support corrosion	Micromycetes and cryophilic bacteria, including iron-reducing and iron-oxidizing, as well as sulfate-reducing species	Local scale	Months and years	Premature wear and progressive failure of mine support
		Shotcrete corrosion	Sulfate aggressivity of groundwater and biocorrosion induced by sulfate-reducing bacteria	Local scale	Months	Premature failure of shotcrete lining
		Biochemical aggressivity of subpermafrost water	Chemical composition of groundwater offers a source of nutritive and energy substrates for growth of microorganism	Everywhere in groundwater	Permanently	Active propagation of biocorrosion in constructional materials in roadways with water ingress
Permafrost rock zone (above levels 300–250 m)						
Exogenous (natural-and-manmade)	Moderate and low	Rock falls	Disintegration of ore body at clusters of tectonic faults given intense jointing	Local scale	Hours	Local instability of face and roof in roadways
		Subsidence of roof and sidewalls during stoping	Violation of backfilling schedule: backfill operations are behind stoping	Local scale	1–7 days	Local displacements in roof and sidewalls
		Higher rate disintegration (jointing) in roof and sidewalls	Drilling and blasting	Super local scale	Hours	Intense rock falls in roof and sidewalls
		Thawing of permafrost	Ingress of warm air in ventilation of mine in the summer period	Local scale	Late June–July–early August	Decreased strength of jointed rocks in roof and sidewalls
		Corrosion of rock bolts and steel mesh	Impact of cryophilic microorganism	On all levels	Months and years	Probability of large-size rock falls
		Corrosion of shotcrete	Impact of cryophilic microorganism	On all levels	Months and years	Intensified weathering of rocks in roof and sidewalls, probability of hazardous gravity-induced processes

consequently, some mesophiles, including sulfate-reducing bacteria, are tolerant to low temperatures and can be taken for cryophiles [10–12].

Visual inspection of steel reinforcement revealed its general corrosion which developed within a very short time (**Fig. 2**).

Figure 3 illustrates point-wise corrosion due to subpermafrost water drip for 4 hours, in combination with slimy incrustation as a result of activity of iron-reducing bacterium *Gallionella ferruginea*. Corrosion of steel is accompanied by biocorrosion of shotcrete.

Cryophiles produce frost-adaptable ferments, which offers an additional substrate for their growth and, at lower temperature, for their life sustaining. Biocorrosion speeds up failure of mine support systems, which, given no special monitoring, can end with large roof falls in mine roadways.

Geological systematization

Origination and evolvement of geological processes is necessary to be predicted in two zones of Kupol mine for the stability assessment in underground roadways and for the safety prediction in mining. After the full-scale and lab-scale studies and analysis, as well as the theoretical generalization, the processes of the natural and natural-and-manmade genesis in the Kupol deposit are systematized in **Table 2**.

Conclusions

1. The uniqueness of geological conditions of the Kupol deposit is governed by the active tectonics and hydrothermal processes in the Upper Cretaceous, which promoted mineralization and high disintegration of petrographic composition of enclosing rock mass.

2. The excessive tectonic stresses recorded below the permafrost strata complicate geological situation at the levels beneath the actual elevation of +300 m.

3. A special place in the subpermafrost strata belongs to groundwater with increased mineralization and high aggressivity relative to mine support materials: steel, concrete and polymers. The experiments prove that groundwater is the major source of microorganisms including micromycetes, iron-reducing and iron-oxidizing bacteria, as well as sulfate-reducing bacteria which generate hydrogen sulfide. These iron-bacteria are cryophilic, and mesophilic (sulfate-reducing) bacteria can be assumed as the tolerant organisms relative to low temperatures in the conditions of nutritive and energy substrates present in groundwater. It should be taken into account that activity of microorganisms stimulates gases, in our case, H_2S and CO_2, as breathing products. These gases are aggressive relative to constructional materials: CO_2 is aggressive to concrete, H_2S is aggressive both to steel and concrete.

4. Biocorrosion processes are hazardous as premature failure of rock bolt systems without implementation of special (one-purpose) monitoring can initiate large-volume falls of jointed rocks, which implicates shutdown and cost escalation.

5. The subpermafrost groundwater constitutes a threat of water invasion and flooding in the mine. For instance, because of high water content of face rocks, the heading advance velocity drops by two times per one cycle as regards the advance velocity of 4.2 m per cycle according to the adopted technical regulations.

6. The systematization of geological processes, accomplished for the first time for the Kupol deposit, can serve as a framework for the development and implementation of the one-purpose integrated monitoring as an observation and safety control tool in underground mining which persistently complicates with increasing depth.

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