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

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 its 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 Kaimraveem 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 irrigations;

• 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 (\(\sigma_2 = \sigma_3\)) 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 Irkodnaya 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 non-tectonic. 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]:
Insert: OCVB in the structure of Northeastern Russia: 1—external zone of OCVB; 2—internal zone (a—sub-zone of graben-synchlines, 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 bytwixt 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, Cenozoic 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 (BOD5). The contents of hydrogen sulfide, sulfates and ammonium should be measured in-situ [5–7].
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 (H₂S) in water was identified during the chemical analysis and by the smell when sampling. The low value of H₂S in the sample is connected with the high oxidation rate of the gas and with the increased content of ion SO₄²⁻. 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 –7 mV and below. The easily oxidized organs 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 BOD₅ 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 Fe⁰ → Fe²⁺, which result in thinning of metal structures. The high content of ion sulfate initiates sulfate corrosion due to formation of calcium hydrosulfoaluminate (3CaO·Al₂O₃·3CaSO₄·3H₂O) 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. Vasov. The microbiological analysis points at the domination of Aspergillus in groundwater and Penicillus, 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

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

**References**

1. Feklistov Y. G., Golotvin A. D., Shirokov M. A. Estimation the workings’ state in kryozone, the Kupol mine being as an example. Problemy nedropol’sovaniya. 2015. No. 4(7), pp. 28–33.