Problems and solutions in underground mining of non-ferrous and precious metal deposits in Yakutia

VP Zubkov and DN Petrov*
Institute of Mining of the North, Siberian Branch, Russian Academy of Sciences, Yakutsk, Russia
E-mail: *petrovdn74@mail.ru

Abstract. The article considers the experience gained in underground mining in Yakutia in terms of geological conditions of local ore bodies, as well as the mining methods used and equipment employed. The main factors of permafrost, having positive and negative effects on the safety and efficiency of mining are identified. The research data on deterioration of underground mining conditions during transition to the subpermafrost levels are given. The solutions proposed make it possible to improve the efficiency of underground mining of ore bodies with lower content of commercial minerals, without infrastructure available and in complex geological conditions, including subpermafrost reserves.

1. Introduction
The analysis of underground ore mining in Yakutia shows high variability in types and characteristics of ore bodies as well as in types and characteristics of enclosing rocks. For instance, Protodyakonov index of hardness in host rocks of non-ferrous and precious metals in Yakutia ranges from 3 to 22 [1, 2].

The deposits are mostly represented by ore bodies and lodes in difficult ground conditions—small expanded and necked areas, apophyses and branchings, faults and folds. The ore bodies are from 0.5 to 3.5 m thick and dip at an angle from 20 to 90°.

The local terrain is mostly mountainous which governs accessing the deposits by means of adits or inclined shafts. It often happens that access to ore is gained via exploration adits and other kind tunnels that are sometimes enlarged for the convenient operation of mining machines.

Ore bodies are usually prepared for mining. In the course of the development and face-entry drivage, the information on occurrence conditions and mineral contents is updated. The amount of work in this case is higher than in the standards, as well as the cost of the support and maintenance of underground openings increases [3].

2. Underground ore mining in Yakutia
Subject to geological and geotechnical considerations, Yakutia mines use mining systems with shrinkage, sublevel stoping, with long extraction panels, with frozen backfill, with delayed installation of support and backfilling (Table 1).

Ore is broken using portable jack hammers and drawn from blocks by scraper loading hoists. Drilling involves no dedusting, thus dust content of air in work areas reaches 600–1000 mg/m³. In mining with long extraction panels, column pillars are left every 20–25 m for the roof support. After completion of stoping in a blocks, scrapers, brooms and a scarper excavator are used for cleaning-up.
Ore is hauled by self-propelling load–haul–dumpers and, sometimes, scarper excavators (in number of 5) to a distance of 100–200 m.

**Table 1.** Brief characterization of geology for some ore bodies in underground mines in Yakutia.

| Mine    | Morphology, dip angle and thickness of ore body | Hardness index of ore / enclosing rocks | Stability of ore / enclosing rocks | Mining system | Dilution of ore / enclosing rocks, % |
|---------|-----------------------------------------------|----------------------------------------|-----------------------------------|---------------|--------------------------------------|
| Badran  | Ore columns; 21–34°; 0.5–3.6 m                | 14–16 / from 3–4 to 14                 | Average stability / unstable      | Room-and-pillar with frozen backfill; room-and-pillar with delayed support installation and dry rock fill | (0–3) / (17–21) |
| Duct    | Echelon lodes; 0–45°; 0.2–3 m                 | 12–18 / 10–16                          | Stable / average stability        | Long extraction panels along the strike | (5–11) / (57–63) |
| Nezhdaninsk | Ore bodies with veins; 55–80°; 0.2–12 m | 15–16 / 15–16                          | Unstable / average stability      | Stoping with shrinkage in blocks under level drifts | (8–12.5) / (17–19) |
| Sarylakh| Ore lodes; 60°; 0.2–5.2 m                      | 9 / 7                                  | Unstable / stable                 | Stoping with shrinkage in blocks | (4.6–6.5) / 30.4 |
| Yursky  | Small-folded lenticular quartz lodes; 0–80°; 0.2–2.5 m | 16–22 / 17–18                         | Stable / stable                   | Long extraction panels along the strike | 8–12 / (49–63) |
| Sentachan| Ore lodes; 50–80°; 0.1–6.9 m                  | 8–9 / 7                               | Stable / stable                   | Stoping with shrinkage              | (9–15) / (15–40) |

Ore hoisting to the surface uses belt conveyors and electrical haulage, sometimes load–haul–dumpers or scarper excavators. Productivity of labor is under 1.0–1.3 m³/man/shift.

Underground mining inflicts no damage to the ground surface, as a rule. The main contamination factors are surface infrastructure of underground mines, gangue stock piles and processing plants.

It is worthy of mentioning that the geological exploration data use mine planning and design show not every fine detail of geological occurrence, shape and structure of the ore bodies. As a consequence, it is typical that many mines produce ore with lower content of useful component due to the systematic overvaluation of ore amount and quality in geological appraisal of deposits [4].

**Table 2.** Key factors of permafrost to affect mining efficiency.

| Factors of heat and moisture content in the permafrost ore bodies | Facilitatory effect | Adversity |
|-----------------------------------------------------------------|--------------------|-----------|
| Higher load-bearing capacity and stability; No groundwater inflow in stopes; Very low gas content and gas permeability; Low-rate oxidation processes in mine and surrounding rock mass under negative temperature | Low temperature in stopes worsens health conditions; Impossibility of using water for dust suppression; Congelation after warm air flow in stopes; Adfreezing of rocks after contact with water or warm air; Increased energy consumption by destruction of rocks; Very low electrical conductivity, which impedes equipment ground |
All deposits occur in the blanket zone of permafrost. The temperature in rock mass varies from –4–5°C (Yursky mine) to –10–12°C (Badran mine). Permafrost has both positive and negative effect on different processes in mining, as well as on safety and efficiency of mines (Table 2).

Furthermore, as mining operations go to deeper levels, in the transition zone (between permafrost and positive temperature rock mass), enclosing rocks become instable, and increased gas content, water content and jointing is observed.

For example, in Badran mine, as soon as mining reached lower boundary of permafrost, stopes began suffering from instability, rock falls and local collapses became frequent, support systems were ruptured in development entries. The research accomplished by the Institute of Mining of the North showed that the strength of enclosing rocks mass was affected by higher temperature and moisture content (ultimate tensile strength reduced from 6 to 2 MPa) [5].

In stoping with shrinkage in Sarylakh and Sentanchan mines, high-rate roof falling was observed in adjacent rocks in the transition zone. In this connection, Sentanchan mine undertook studies aimed to revaluate parameters of stopes. According to the research findings, frozen rocks and ore have rather high strengths in compression and tension. However, under thawing, milonitized siltstone in the zones of schistocity becomes 5 times weaker while antimonite ore preserves its strength characteristics [6].

Instability of enclosing rock mass grows with depth and is a feature of all ore deposits in the zone of permafrost [7–9].

The geological deterioration in combination with the disagreement between the geological appraisal and factual amount and quality of ore reserves in the conditions of mining without infrastructure and permanent transportation routes considerably reduce cost efficiency of mining.

One of the ways of improving performance of ore mines is application of systems with cemented backfill that are very popular in the similar geological conditions in Alaska, Canada and Norway [10–12]. Unfortunately, the use of cemented backfill in Yakutia is complicated by the high cost of materials and total absence routine transport services.

The efficient underground mining of ore bodies in Yakutia requires scientifically sound and resource-saving technologies adaptable to the conditions of permafrost. The Institute of Mining of the North, after the integrated research of thermal and moisture conditions, as well as the systems of mining in permafrost, offers some guidelines towards prompt response to variation in geological situation and the desired completeness of ore extraction [13].

For example, if exposed frozen enclosing rocks are stable, it is efficient to use the system of stoping with shrinkage. At the same time, in subpermafrost mining, this system is inefficient as the enclosing rock mass is unstable, and secondary dilution and ore loss increase. In the latter conditions, for the best mine performance, it is suggested to use the system of stoping with shrinkage and a flexible canopy. Based on the findings of lab-sale research and data of full-scale testing in Bakyachi mine in Kazakhstan and Nezhdaninsk mine in the Republic of Sakha (Yakutia), the Institute of Mining of the North has designed and manufactured a flexible synthetic canopy. The design of the canopy is protected by the author’s certificate. The capacities of the put forward alternatives for mining in different geological conditions of ore bodies (dip angles 70–90°, thickness 2.5–5.5 m) were tested in the lab-scale physical modeling of the ore draw. The process solutions developed based on the test results enable ore loss to be decreased by 2 times and ore dilution to be reduced by 5 times as compared with the process of ore drawing without the canopy.

Badran ore mine used the room-and-pillar method of mining, which failed to ensure completeness and quality of gold extraction. The loss and dilution of gold reached 28–30 and 30–35%, respectively. Aiming to reduce gold ore loss and dilution in Badran mine, the Institute of Mining of the North has developed and introduced at a commercial level the system of room-and-pillar mining with the delayed frozen backfill. By now, mining with this system has produced more than 900 thousand tons of gold ore at the loss of 0–3% and dilution of 17–21%. After accomplishment of the integrated theoretical and experimental investigations, the recommendations on the design and implementation of frozen backfilling are made.
There some ore deposits in Yakutia, for instance Nezhdaninsk gold ore, Sarylakh and Sentachan antimony–gold ore, Upper Menkeche silver–lead–zinc ore, which allow using various systems of mining with caving owing to specific occurrence. The systems with caving feature high productivity and comparatively low cost, which make them profitable in mining ore bodies with low content of useful components given no essential expenditures connected with the ground control [14, 15]. Nonetheless, in order to apply this technology in the conditions of Yakutia, different constraints of underground mining should be analyzed, for instance, possible adfreezing of broken ore in stoping area.

For the assessment of the effect exerted by thermal and moisture conditions on mine performance in permafrost zone, it was studied how the time of holding broken ore prone to adfreezing in stoping area affects the ore loss in case of different moisture content of the ore. The broken ore loss due to adfreezing grows considerably as its moisture content rises from 0.5 to 1.0% at the time of holding the ore in the stoping area for longer than 1 day. Thus, at this stage of the studies, it is possible to handle the problem of ore adfreezing by reducing the time of its holding in stopes.

The determined relationship between the moisture content and loss of ore will be used in development of recommendations on draw technologies of ore prone to adfreezing in the conditions of negative temperatures in underground mine in the permafrost zone.

3. Conclusions

1. The current situation in underground ore mining in Yakutia is characterized with the deterioration of geological conditions, inconsistency of the geological appraisal and actual quality and amount of ore reserves, as well as with total absence of surface infrastructure and permanent transportation routes, which drastically degrades efficiency of conventional underground mining technologies.

2. The variation in the strength and stability of permafrost rock mass depending on temperature is the key cause of reduction in underground mine performance in the permafrost zone. Accordingly, it is required to develop appropriate programs for monitoring changes in strength, stability and temperature of rock mass as mining front goes to deeper levels.

3. The profitability of underground ore mines in Yakutia to be risen calls for a package of measures, including managerial and technical, based on the scientifically sound and resource-saving technologies with regard to specific occurrence conditions of ore bodies in the permafrost zone.

References

[1] Tkach SM 2006 Methodology and Geotechnology for Improving Efficiency of Mining Ore Deposits and Placers in Yakutia Yakutsk: IMZ SO RAN (in Russian)
[2] Tapsiev AP and uskov VA 2014 Development of mining methods for the thawed zone conditions of the Nezhdaninskoe gold deposit Geo-Sibiria & Expo–2014: Conference Proceedings Novosibirsk (in Russian)
[3] Kursakin GA 2002 Technology of Mining Gold Veins Vladivostok (in Russian)
[4] Romanova ER and Batugina NS 2016 Mining industry in the economy of the Republic of Sakha (Yakutia): State-of-the-art, problems and challenges Gornyi Zhurnal No 9 pp 23–26
[5] Neobutov GP, Zubkov VP and Petrov DN 2014 Stability of rock exposures in underground mines in permafrost Nauchnoe Obozrenie No 8 pp 941–944
[6] Petrov AN and Nikiforov LA 2011 The experience of underground mining in Santachan gold–antimony deposit GIAB Special Issue 10 pp 185–191
[7] Klishin VI and Vlasov VN 2002 Problems of underground mining of kimberlite deposits in permafrost zone Permafrost Engineering: V Int. Symp. Proc. Yakutsk Vol 2 pp 12–15
[8] Pavlov M, Semenov YuM, and Sosnovsky LI 2014 Design of stable pillars and rooms for underground mining of inclined veins in Irokinda gold mine in the conditions of permafrost GIAB No 10 pp 21–27
[9] Iudin MM 2011 Effect of geo-cryology on underground ore mining in the North GIAB Special issue 10 pp 97–101
[10] Coil D et al Gold Mining Methods Available at: http://www.groundtruthtrekking.org/Issues/MetalsMining/GoldMiningMethods.html

[11] Scales M 2012 One of a kind. Lac des iles palladium mine expands Canadian Mining Journal February–March pp 22–24

[12] The Bjørkdal Mine. Underground Mining. Horn International 2015 Available at: http://hornonline.com/the-bjorkdal-mine

[13] Zubkov VP, Neobutov GP and Petrov DN 2017 Enhancing completeness and quality of underground gold ore extraction in the Republic of Sakha (Yakutia) Gorny Zhurnal No 4 pp 53–56

[14] Evertovsky VM 2014 Systems of underground mining with bulk caving at Irgiredmet Zolotodobycha No 193 Available at: http://zolotodb.ru/news/11164

[15] Savich IN and Mustafin VI 2015 Prospects and designs of block and sublevel caving GIAB Special Issue 1 pp 419–429