Sublevel caving under protection of ore-and-barren rock cushion during transition from open pit to underground mining

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Abstract. These studies aimed to evaluate an efficient method of ore mining under open pit bottom during transition from open pit to underground mining. In the transition period and further mining with the sublevel caving method, it is proposed to use a protection in the form of an artificial large-block ore-and-barren rock cushion (capping) created by partial caving of benches and bottom of open pit. The analytical calculations and modeling performed for optimizing parameters of geotechnology and ore discharge provide indexes of ore recovery completeness and quality.

1. Introduction

In modern conditions of intensification of mineral production at increasingly deeper levels, it is a common practice to transit from open pit to underground mining. In this connection, it is highly important to develop and introduce safe methods for recovery of ore reserves under open pit bottom with further efficient transition to deeper levels.

Operating mines all over the world have accumulated ample experience of mining under open pit bottom using systems with caving and backfilling. Mines that have efficiently implemented the hybrid mining method include Zyryanovsky, Gaisky, Sheregesh mines, etc, in Russia, krivoi Rog basin mines in Ukraine, Questa in USA, Finsch and Bellezane in South Africa, Vammala in Finland, Hemlo and Kidd Creek in Canada, and many other [1–4].

The hybrid mining features high probability of pitwall rock fall in underground mine. The disruptive effect of the rockfall can be prevented using cut-and-fill systems, or by creating a safety pillar between the open pit and underground mines [5–7]. These measures make mining expensive and dependent on backfill material supply. In addition, considerable ore resources are left in the protective pillar.

In this regard, it seems efficient to mine ore reserves under open pit bottom by the system with sublevel caving. The stoping face is continuously regenerated, and ore is discharged under caved rocks, which enables sufficient stability of stopes and controllability of mining operations [8–12]. Caved rocks offer a protection layer to counteract probable rock fall from open pit to mined-out stoping void, as well as contribute to better ventilation in underground mine. Furthermore, sublevel caving method features simple preparation of rock mass for stoping, high productivity, low cost, adaptability of single-type machines to heading and extraction, and is efficient in medium-grade ore...
bodies [13]. Disadvantages of sublevel caving include high loss and dilution variable in wide ranges of 7.8–15.5 and 9.0–27.0%, respectively.

In such conditions of hybrid mining, the backbone of engineering solutions aimed to ensure efficient sublevel caving at the stage of transition from open pit to underground mining is improvement of ore recovery completeness and quality factors, i.e., reduction of ore loss and dilution. The major avenues towards this objective are:

— optimizing SCL method parameters to fit with specific deposit (sublevel height, cavable layer thickness);
— modifying SLC design (shaping stoping zone as ellipse, trapezoid or rhomb).

This study aimed to find rational parameters and improve ore recovery indexes during sublevel caving under open pit bottom using a large-block protection capping made of broken ore and barren rocks of the open pit bottom and walls.

2. Mining under open pit bottom
In sublevel caving under open pit bottom, the ore body is split into sublevels with a height \( h = 15.5–28.5 \text{ m} \) (Fig. 1). Broken ore is drawn from sublevels via ore chutes to haulage level and, then, to skip hoisting shaft. As a rule, stoping is divided into two stages: the first stage is extraction or ore reserves adjoining open pit (sublevels 1 and 2); the second stage comprises the bulk of the deposit (deeper sublevels).

In sublevels 1 and 2, coarse drilling pattern is designed so that to size open pit bottom and walls, and blasting is performed so that to produce coarse fragmentation to create a large-block ore-and-barren rock cushion [14]. Broken ore is either never or partly drawn (not more than 50%), and sublevel caving is continued under protection of the cushion.

During the first stage sublevel caving, the ore-and-barren rock cushion can gradually accumulate at the footwall of the ore body and get thinner at hanging wall. In order to keep initial thickness of the cushion at the hanging wall, a few last layers of broken ore under the hanging wall should be never or limited discharged so that some ore and rocks is left to renew the cushion. Accordingly, in case of ore
extraction immediately under open pit bottom, ore drawing modes should be set based on the preservation of the initial parameters of the ore-and-barren rock cushion (capping), while in deeper level mining—based on the minimum penetration of barren rocks from the cushion and rational reasoning of ore loss and dilution.

![Figure 2. Sublevel caving under open pit bottom: 1—large-block ore-and-barren rock cushion; 2—broken ore; 3—caved rocks; 4—drilling-and-haulage drift; 5—ore and rock chute; 6—haulage level; 7—blastholes; 8—remaining ore.](image)

The proposed technology eliminates caving of enclosing rocks onto the large-block capping. At the same time, during sublevel stoping, it is possible that pitwalls and exposed rocks of the handling wall and footwall, or undermined top ore partly cave and accumulated on the large-block cushion. Barren rocks can penetrate from this layer into the cushion and result in an increase in ore dilution later on. The nature and condition of the barren rock layer on the cushion should be persistently monitoring, and this is a mandatory requirement of the proposed technology to be efficiently applied. According to mining practice in Zyryanovsky and Gaisky mines, granulometric composition of the large-block ore-and-barren rock cushion should be composed of fraction ranging between 0.4 and 1.2 linear size of a stope. As sublevel caving is advanced, depending on safety of the protection pillar, condition of sidewalls in mined-out voids and mining safety requirements, partial caving of enclosing rocks in the hanging wall is admissible.

Lumped calculation of the protective cushion pillar at different depths in the worst caving conditions [13] show that ore recovery at a depth of 30–120 m below open pit bottom, the minimum thickness of the protective cushion is 18.7–48.4 m.

### 3. Rational parameters of mining system

Transition from open pit to underground mining is possible in stable enclosing rock mass. Sublevel caving with ore drawing from drilling-and-haulage drifts can only be safe under a protective cushion made of broken ore and barren rocks. Thickness of this protective cushion should never change in the course of mining, which is ensured by adhering ration mode of ore discharge.

In case that the protective cushion is composed of broken ore, the advised mode of ore drawing is preserving equal volumes of ore discharge and ore reserves in a layer:

$$ V_{layer} = K_{loose} V_{draw}, $$  

where $V_{layer}$ is the volume of ore reserves in a layer, $m^3$; $K_{loose}$ is the loosening coefficient of broken ore, $m$; $V_{draw}$ is the volume of ore drawing, $m^3$.

Equality (1) is the framework to determine height of an ore draw point (shaped as an ellipsoid):
where $S_l$ is the area of the broken layer, m$^2$; $t_l$ is the thickness of the broken layer, m; $\rho$ is the flowability index, m.

Relation (2) makes it possible to calculate quantity of broken ore left in a stope to create a constant-thickness protection cushion and is valid for ore with average metal content over the deposit (found out experimentally). However, it happens during stoping that a part of ore is cut under caved rocks due to discontinuity of the protection layer (Figure 2, right-hand side).

No matter how variable geotechnical conditions are, the major criteria of efficient mining is the maximum recover of ore reserves at the minimum cost. The rational parameters of the sublevel caving system are calculated based on the analytical studies with some assumptions made. It is assumed that ore is extracted in diamond-shaped panels. The protective cushion (capping) is created by means of partial shrinkage of broken ore over the period of extraction of certain portion of ore reserves.

The ore recovery characteristics were calculated for the conditions of ore drawing under caved rocks and under the protective cushion composed of large ore and barren rock blocks. The draw point parameters (Figure 3) were correlated with the loosening coefficient, flowability index, ratio of sublevel height to spacing of drilling-and-haulage drifts and with the layout of sublevel stopes.

\[
H = \sqrt[\pi\rho]{\frac{3S_l t_l K_{\text{loose}}}{\pi\rho}},
\]

Efficient parameters of the hard ore mining system were selected with respect to relative net profit per 1 t of in-place reserves. Variable operating cost of mining was chosen subject to the change in the diamond-shape panel parameters and the associated specific volumes of development and heading operations. Drilling-and-blasting ad other operating costs of ore mining and processing were assumed to be constant. The calculation algorithm of ore recovery characteristics and the value of profit per mining variants were, respectively, based on the ore drawing patterns under caved rocks from draw
points shaped as ellipsoids of revolution (Figure 3) and on the parametric modeling of structural elements within the mining system (sublevel height spacing of drilling-and-haulage drifts and thickness of broken ore layer).

The calculation results made it possible to determine efficient parameters for sublevel caving in diamond-shaped panels in different conditions of ore drawing at the minimized ore loss and dilution:

\[
\ell_{\text{layer}} \approx \left(\frac{2}{3}\right) \frac{h}{\sqrt{1 - R}} \rho, \quad (3)
\]

where \( R \) is the limit dilution in the last ore draw portion, unit fractions,

\[
L = 2 \left( \frac{h}{\tan f} + b \right) + \frac{b}{4}, \quad (4)
\]

\[
f = \arctg \left[ \frac{2h}{3\left(\sqrt{h\rho} - \frac{b}{2}\right)} \right]. \quad (5)
\]

A reasoned ratio of sublevel height to broken ore layer thickness is governed by the latter parameter, ranges as 3–6 and is on average 4–5.

Sublevel caving under protective ore-and-barren rock cushion, owing to extraction of “cleaner” ore as against ore drawing under caved rocks, allows expanding the net of stopes by 15–20%. By the criterion of relative profit in this case, the optimized variants are the panel width to sublevel height ratios ranging from 0.85 to 1.5 (Figure 4).

\[\text{Figure 4. Net profit per 1 t of in-place reserves versus ratio of stoping caving system parameters: 1—ore drawing under protection ore-and-barren rock cushion; 2—ore drawing under caved rocks.}\]

The calculations have determined efficient mode of ore drawing under protection of ore-and-barren rock cushion. The required thickness of the cushion is maintained by drawing its part equaling the remaining part (11–22%) after discharge of basic reserves from the extraction panel (78–89%). This measure makes it possible to maintain the thickness of the large-block cushion for the whole period of safe mining at minimized cost.

4. Conclusions
The implemented analytical studies have determined optimized ratio between the mining system parameters for the stage of transition from open pit to underground mining and efficient modes of ore drawing to preserve continuous thickness of large-block ore-and-barren rock cushion and the required mining safety. The key recommendations on application of the proposed technology say that:

—ore extraction panels should be shaped as diamonds at most escribed into ellipsoids of revolution;
—coarseness of fraction of the protective ore-and-barren rock cushion should be set not less than 0.4–1.2 of maximum linear size of a drilling-and-haulage drift;
—volume of ore drawing should be 40–50% of broken rock volume from panels in the first and partly second sublevels immediately under open pit bottom and 100% from the lower lying sublevels.

In the course of underground mining, the proposed parameters of sublevel caving system will be continuously updated with regard to the change in the depth of mining and in the flowability index, which nonlinearly diminishes with the growing depth of mining due to compaction and compression of rocks.

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References
[1] Farafonov VP 1984 Experience of hybrid mining in Gaisky deposit Gornyi Zhurnal No 4 pp 13–15
[2] Jalonen M, Forster D et al 2013 Global Gold & Precious Metals Merrill Lynch 09 April USA
[3] Barnov NG, Eremenko VA, Kondratenko AS and Timonin VV 2015 Substantiation of parameters of geotechnology for mining primary corundum deposits in difficult working conditions in upland areas Gornyi Zhurnal No 11 pp 42–47
[4] Neverov AA, Konurin AI, Shaposhnik YuN, Neverov SA and Shaposhnik SN 2016 Geomechanical substantiation of sublevel-chamber system of developing with consolidating stowing 16th International Multidisciplinary Scientific Geoconference—SGEM 2016: Science and Technologies in Geology, Exploration and Mining Vol II Albena, Bulgaria pp 443–450
[5] Freidin AM, Neverov SA, Neverov AA and Konurin AI 2016 Geomechanical assessment of geotechnology at a project stage of underground ore mining Gornyi Zhurnal No 2 pp 39–45 DOI: 10.17580/gzh.2016.02.08
[6] Lushnikov VN, Sandy MP, Eremenko VA, Kovalenko AA and Ivanov IA 2013 Method of definition of the zone of rock massif failure range around mine workings and chambers by numerical modeling Gornyi Zhurnal No 12 pp 11–16
[7] Shaposhnik YuN, Konurin AI, Neverov SA, Neverov AA, Shaposhnik SN 2016 Justification of mine working supports in terms of the rating classification of Norwegian Geotechnical Institute 16th International Multidisciplinary Scientific Geoconference—SGEM 2016: Science and Technologies in Geology, Exploration and Mining Vol II Albena, Bulgaria pp 519 – 526
[8] Balg C, Roduner A and Geobrugg AG 2013 Ground support applications Int. Ground Support Conf. AGH University, Lungern, Switzerland
[9] Reiter K and Heidbach O 2014 3-D geomechanical-numerical model of the contemporary crustal stress state in the Alberta Basin (Canada) Solid Earth No 5(2) pp 1123–1149
[10] Günzburger Y and Magenet V 2014 Stress inversion and basement-cover stress transmission across weak layers in the Paris basin, France Tectonophysics Vol 617 pp 44–57
[11] Hofmann H, Weides S, Babadagli T, Zimmermann G, Moeck I, Majorowicz J and Unsworth M 2014 Potential for enhanced geothermal systems in Alberta, Canada Energy No 69 pp 578–591
[12] Potvin Y and Giles G 2008 The development of a new high-energy absorption mesh Australasian Institute of Mining and Metallurgy Publication Series pp 89–94
[13] Imenitov VR, Abramov VF and Popov VV 1983 Localization of Voids in Underground Ore Mining Moscow: Nedra (in Russian)
[14] Timonin VV and Karpov VN 2016 Assessment of rock failure process under percussion–rotary drilling from the viewpoint of nonlinear geomechanics J. Fundament. Appl. Min. Sci. Vol 2 No 3 pp 172–176 (in Russian)