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PECULIARITIES OF TECHNOLOGICAL DEVELOPMENT AT THE CLOSING STAGE OF MINING OF PROVEN RESERVES*

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The closing stage of mining is characterized by the induced alteration of minerals, which entails aggravating environmental, geotechnical and geomechanical effects that complicate mining production activities. Efficient decision-making in this case depends on innovation of mineral mining and processing technologies, increment in mineral reserves owing to refinement of quality standards as well as on reorganization of mining companies. The maximum efficiency to be reached at the closing stage of production requires using the whole resource potential of the subsoil area under development — standard quality ore and waste, off-grade ore and nonmetallic associates, middlings of processing circuits, current tailings, old mine waste, mined-out voids, and power and heat generation utilization products. It is important to emphasize that such mineral reserves are altered as a consequence of long-term mining activities, occur in concentration zones of shear and normal stresses, or in the zones of weakening and fall of enclosing rocks, and are subjected to secondary structural and compositional changes. The best mineable ore is already extracted, and the remaining reserves occur in local pinchouts, in production-altered areas with the old elements of timber support and in safety pillars. Such reserves are characterized by lower content of valued components as compared with the average grade of proven reserves, and by more difficult geotechnical and geomechanical conditions. Regarding some mineral deposits repeatedly put under mining, the geological and technical documentation data are lost, which entails new complications connected with the necessary geological exploration and justification of mine-technical system parameters. All that calls for a new more responsible approach to the conceptual baseline and to selection of a technology for the closing stage of mining when 75–80% of proven reserves have already been extracted.

Key words: *technological development, late mining stage, extraction, proven reserves, planning, georesources, reorganization*

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Introduction

The late phase of mining when proven reserves are extracted to 75–80% is currently typical for the majority of large strategic mineral deposits in Russia. Mining science has no unique definition of the closing mining stage. It is generally recognized that pursuant to the diversity and multifunctionality of mineral wealth or georesources, the closing stage of extraction of proven reserves is not so critical, and is not necessarily accompanied by the decrease in the rate of work until the complete closure of a mine but can be a new turn of technological development. The socio-economic determinants of the aforesaid are described below:

— mining towns and urban-type communities were once formed for the development of certain mineral deposits; thus, mining is a town-forming business, and closure of such mines entails sever social impact connected with the unemployment;

— being operated for many years, mines and processing plants have accumulated colossal quantities of mining and processing waste on the ground surface: low-grade ore stockpiles and overburden dumps; tailings ponds of processing and metallurgy; slurry ponds; corrosive water settling ponds; and mined-out voids. In case of mine closure, these waste bodies loose an owner, and their environmental impact becomes uncontrollable;

— construction and operation of mines consumes high investment, including open pits the depth of which is comparable with the height of skyscrapers, as well as dumps etc. Such mine-technical objects can be used in various industrial, social and agricultural purposes;

— after extraction and processing of minerals and raw materials, rock mass containing many different less valued components is stored and exposed to weathering, leaching, erosion and other induced alterations that bring irreversible damage to the environment.

In order to avoid these negative phenomena, the late phase of mining of proven reserves should be assumed not the mine pre-closure stage but the next period of technological progression of the mine within a new conceptual framework.

Methodological prerequisites of technological development in the late phase of mining of proven reserves

It is known that the life cycle of any object contains stages of initiation, growth, stable development and dying out.

A mine targeted at integrated development of a subsoil area rather than merely licensed mineral mining should use all georesources contained in this area to the maximum efficiency. According to Agoshkov's classification, mineral wealth is represented by a wide variety of georesources (**Table 1**).

It is important to highlight that mineral deposits, even at the closing stage of mining of proven reserves, contain considerable natural inorganic stock as well as huge accumula-

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tions of production waste and other georesources suitable for the efficient development in the future. The internal parts of the earth hold natural and production-induced reserves in various purpose pillars, in backfill, caving zones, at deeper levels and in remote areas, and in pinchouts. Furthermore, there are low-grade ore stockpiles, waste dumps, mined-out areas and mining-generated landscape. Sometimes, proven reserves are increased as a result of operational exploration [1].

On the other hand, at the closing stage of mining, all reserves are technologically altered, which initiates negative geological, geotechnical and geomechanical events complicating mining operations. However, there are positive trends connected with the scientific and technical advance in mineral mining and processing, in the mineral market, and in social and taxation spheres, including changes associated with toughening of the environmental requirements. Considering the influence of these factors at the stage of completing mine design solutions, it is required to undertake auditing of the whole resource potential in the subsoil area under development, to indentify prospects and to frame a concept of a new cardinally different mine. The economic justification of the concept should adhere to the equilibrium between the economic interests of a subsoil owner, commercial interests of a subsoil user and social interests of population in the industrially developed regions exposed, as a rule, to the sever industrial and environmental load [2, 3].

Duration of a mine life cycle depends on the mine management capacity to attain dynamic equilibrium with the external environment. The dynamic nature of the equilibrium makes the mine performance stable in time and space. Given the steady disequilibrium, the process of destruction is initiated up to the complete closure. Stability of a mine-technical system at its closing stage in the framework of audit of all georesources (**Fig. 1**) can be ensured by implementation of modernization, suspension, re-extraction of mineral reserves, diversification, technical retooling and resource reproduction [4].

Table 1

I	One-component and multi-component mineral deposits;
II	Geological material, overburden and enclosing rocks (in underground mining), total reserves extracted and stored separately, dirt from partings extracted together with profitable mineral and sent to the further processing;
III	Mineral production and processing waste; Mining, processing and metallurgy waste;
IV	Underground fresh, mineral and thermal water;
V	Heat of the Earth;
VI	Natural and anthropogenic (production-caused) voids in the subsoil — mined-out voids;
VII	Reproducible energy from geotechnical sources.

The off-grade natural and production-induced resources can be added to the balance sheet of a mine in case of:

— availability of break-through technologies of mineral mining and mine waste management;

— adaptation of the known approaches to the specific deposit conditions at the closing stage of operation;

— social demand connected with the subsoil user's decision on the extension of limit of efficient performance of the mine;

— deficiency of capital and operating inputs in construction of new mines to extract the same kind mineral raw material, due to intensive replenishment of mineral and raw materials supply base of operating mines;

— variation in the metal market conditions subject to the fulfillment of one or several conditions listed above.

In order to ensure the technological development of a mine at the late stage of complex ore mining and associated waste management, it is necessary to introduce a full geotechnical cycle, including combination of underground mining, separation, concentration, heap, in-place and low-temperature agitation leaching, hydrometallurgy and backfilling

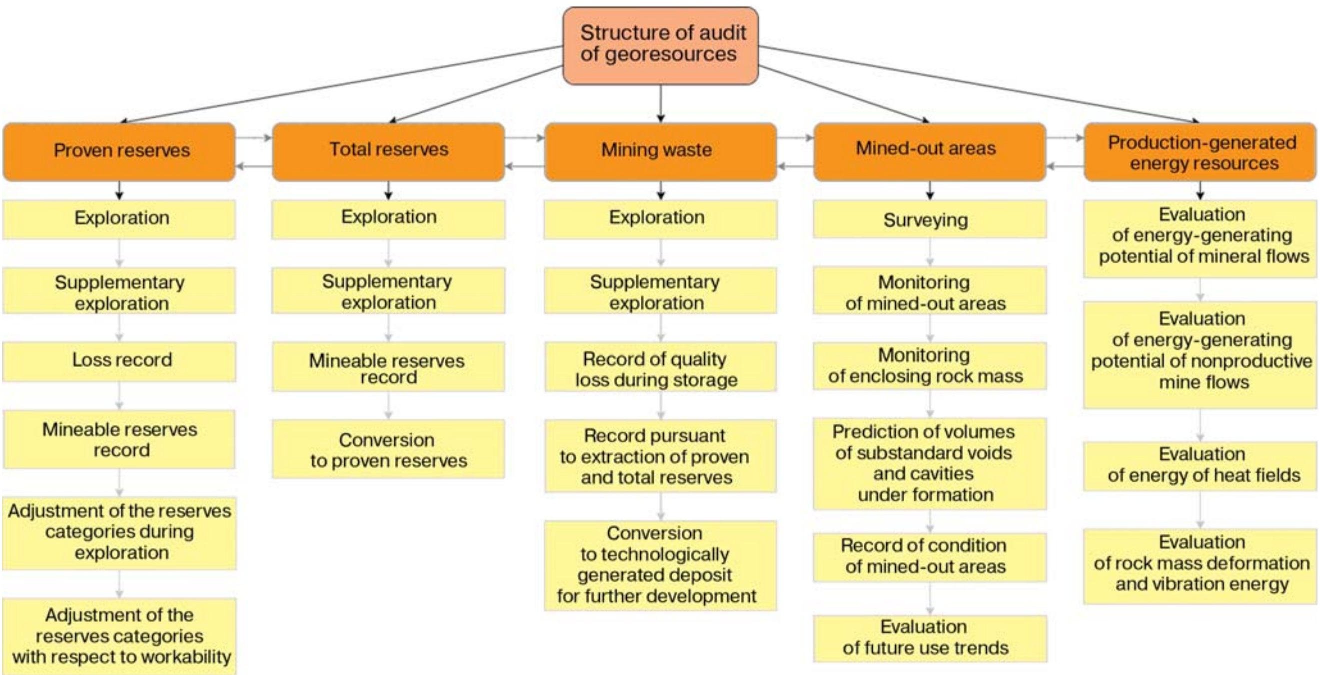

Fig. 1. Structure of auditing of georesources

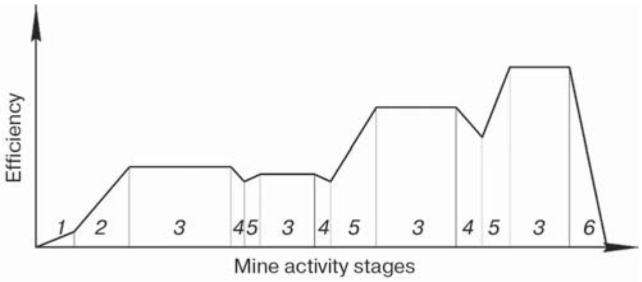

Fig. 2. Stages of mine activities in integrated development of mineral resources:
***1* — initiation; *2* — growth; *3* — stabilization; *4* — dying out; *5* — re-organization; *6* — closure**

of mining and processing waste. Incidentally, requirements for products and performance of individual subsystems — raw material, mining, pretreatment and processing by-products and waste — are changed for the convenience of the most efficient and complete use of the resource potential of the subsoil area under development. In this case, in view of inexhaustible mineral wealth, the action period of a mine can consist of a number of life cycles (**Fig. 2**).

Based on the accomplished auditing of georesources towards the ecological efficiency of mine-technical systems at the closing stage of mines affiliated to the UGC Gold Mining Company (hereinafter UGC), the feasibility of extraction of low-grade natural minerals and management of mine waste in line with the proven reserves development; recycling of mining and processing waste as backfill; utilization of mined-out voids and production-induced landscape as well as the implementation of energy reproduction technologies has been studied [5–7].

Technological development at UGC at the closing-stage gold mining: Problems and solutions

Gold mining industry in Russia is currently faced with the serious difficulties connected with the limited proven gold ore reserves, which necessitates extension of efficient activities of mines at the late stage of extraction of proven reserves through development of low-grade ore left in the early mining stage in various purpose pillars, mineralized zones in hanging walls and footwalls of gold veins, at deep levels, in the concentration zones of the tectonic subhorizontal and gravitational vertical stresses, and in gold production waste accumulated in the tailings ponds during many centuries of mining [8].

It is important to highlight that these mineral reserves have been altered as a consequence of long-term operation of mines, are in the zones of relaxation or concentration of shearing and normal stresses, or in the zones of weakening and caving of enclosing rocks, and are subjected to the secondary alteration of structure and material constitution. The best recoverable ore is already extracted, but there are local pinchouts, altered areas with elements of timber support and safety pillars left underground. All these areas feature lower content of valued components as compared with the average content of valued components of proven profitable reserves and occur under more difficult geotechnical and geomechanical conditions. Moreover, there is no geological or technical documentation on some old deposits many times involved in development, which initiates additional problems connected with geological exploration and feasibility study of mine-technical system parameters.

Thus, a new and responsible approach is required to justify the mining concept and selected technologies for the late stage of mining when 75–80% of proven reserves have been extracted.

With regard to the positive tendencies associated with the scientific and technical advance in mineral mining and processing, with the variations in the mineral market, and in social and taxation spheres, as well as with the strengthening of the environmental requirements, UGC have implemented auditing of all resource potential of the subsoil areas under mining (**Fig. 3**) and elaborated a development framework under the changed conditions [9, 10].

It is noteworthy that mining operations at the most of UGC deposits were started in the 19th century, which conditions extra negative geological, geotechnical and geomechanical events and even effect of historical factors, and

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Geological appraisal	Selection of mining system	Integrated ore and mine waste testing	Determination of potential processing methods	Ecologo-economic justification
		Analysis of material constitution, structural characteristics and physical properties	Preparation of raw material to pre-treatment, flotation	Environmental research, economic assessment of technologies
• Reserves evaluation; • Mapping; • Sampling; • Evaluation of content of gold, harmful admixtures	• Sublevel stooping; • Shrinkage stoping; • Second mining with in-stone development; • Cut-and-fill mining; • Block leaching	• Chemical and phase composition analysis; • Mineralogical analysis; • Image-analysis; • Grain-size composition analysis; • Moisture, porosity, hardness, density and water absorption ability testing	• Grindability analysis, beneficiation and leaching process designs; • Selection of flotation agents and composite leaching agents Secondary treatment of processing and leaching products	Evaluation data on environmental impact severity and nature in case of the generally balanced eco-cycle

Fig. 3. Steps of auditing of mineral reserves at the closing mining stage

calls for the special approach to mining safety. At the same time, despite the fact that the majority of the reserves have been extracted due to some objective geotechnical reasons (reduced replenishment of resource base of mining, lower quality of produced minerals, depletion of large deposits, deterioration of climatic conditions in areas of new mines, etc.) as well as positive technological and socio-economic factors (new technological capabilities in mineral mining and processing, development of resource-reproductive geotechnologies, positive trend in the market of precious metals, etc.), UGC facilitates and promotes expediency (for socio-economic reasons) of restructuring, reorganization and reequipment of mines with the expansion of geotechnical cycle up to production of highest purity gold [11–15].

The implementation is only possible in the framework of updated strategic solutions on development with the auditing of all georesources in the subsoil areas under mining based on the principles of resource reproduction; integrated geomechanical and production research with respect to individual kinds of natural gold-bearing materials and mine waste in order to select efficient systems and technologies for getting access to mineral bodies, for mining of veins and mineralized pockets, for integrated and deep conversion of high-grade and off-grade ore with the recycling of waste in backfilling mined-out voids towards efficient ground control in the course of mining.

The elaboration and efficient implementation of such strategy necessitates pushing the limits of the integrated development of mineral resources with inclusion of process previously unrelevant for mining production:

- Heap leaching of valued components from off-grade natural material and mine waste;
- In-place separation of off-grade ore;
- In-place leaching in local ore bodies or pinchouts;
- Granulation and pelletizing of finely dispersed mine waste material;
- Calcinations and physicochemical pre-treatment of off-grade material;
- Ore pre-treatment to recover preliminary concentrates;
- Agitation and low-temperature leaching of middlings;
- Hydrometallurgical treatment of pregnant solutions with the complete recovery of all valued components into the marketable metal products;
- Thickening and dewatering of mine waste for paste backfill production;
- Aeration and decontamination of tailings and pulp slurry;
- High quality and fine purity marketable production;
- Development of a complete closed-cycle nonwaste technology.

Conclusion

Such strategy accepted by the UGC Gold Mining Company allows sustainable development for the sake of preservation of mineral wealth, efficiency of mines–subsoil users and safety of population in mining regions. Moreover, after converting potential resources into proven reserves, the Company will have all opportunities both to hold and enhance its gold market power.

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