UDC 551.1/4 (073)

A. G. SEKISOV[1,2], Deputy Director, Chief Researcher, Doctor of Engineering Sciences
Yu. P. PANOV[3], Acting Rector
O. S. BRYUKHOVETSKIY[3], Professor, Doctor of Engineering Sciences, bryhovetskyos@mgri.ru
A. V. RASSKAZOVA[1], Leading Researcher, Candidate of Engineering Sciences

[1]Institute of Mining, Far Eastern Branch, Russian Academy of Sciences, Khabarovsk, Russia
[2]Transbaikal State University, Chita, Russia
[3]Sergo Ordzhonikidze Russian State Geological Exploration University, Moscow, Russia

PROMISING GEOTECHNOLOGIES FOR GOLD PLACER MINING IN EASTERN TRANSBAIKALIA

The Transbaikal Region holds a large stockpile of gold reserves in placers. Gold placers differ in structural tectonics, morphology and parameters of productive strata, their specific mineralogical and geochemical composition, grain-size composition and shape of gold grains, roundness and fineness of gold particles, etc. The drop in the gold content and thickness of productive sand at placers being currently mined necessitates studying refractory gold, including encapsulated, dispersed and chemically bound gold. This article discusses new patent-protected methods for identifying nanoscale gold. New geotechnologies for gold extraction from placer sands using solutions with active chloride complexes pumped into productive formations via wells are presented. Alongside with pumping out pregnant solutions, it is proposed to use the electro-diffusion deposition of dissolved gold from a conventionally immobilized pore solution onto ion-exchange resins placed together with submersible cathodes in wells.

Keywords: *gold alluvial deposits, chloride–hypochlorite leaching, well (borehole) geotechnology*
DOI: *10.17580/em.2022.02.08*

Introduction

The Transbaikal Region has been extracting gold from placers since 1851. Eastern Transbaikalia is one of the oldest gold-producing regions in Siberia and is Russia's largest source of prime minerals. This region holds many gold-bearing placers [1]. Mining practices use different methods to extract gold from Transbaikalian placers: opencast and underground mining, trenching and dredging. The currently prevailing methods are the conventional opencast mining with stripping of peat and sand by dozers, after which follows sluicing with recirculated water, and the dredging method on a smaller scale [2].

These methods of placer gold mining are insufficiently effective as they leave intact solid blocks with low content of gold or with small thickness of productive beds, and since many gold fines and flakes are lost in sluicing. Furthermore, the loss of chemically bound disperse and encapsulated gold localized in placer sand is especially high. In this respect, it is fairly necessary to find new mining methods for such placers, using physicochemical techniques of gold recovery both from the conventionally extracted productive sand and in situ, with application of activated process solutions and with stimulation treatment of the mineral environment. The known nonstandard methods to analyze gold-bearing raw materials, developed in USA and in Russia [3], enable reliable detection of chemically bound nano particles of noble metals in natural and manmade-transformed minerals. The integrated mineralogical, geochemical and geotechnical research of samples taken from gold placers in Transbaikalia, as well as from dredging and sluicing tailings, and from gold washing sludge often revealed chemically bound gold [4, 5]. It is also frequent that gold occurs in bimetal gold–silver bullion [6].

Academician V.G. Moiseenko together with colleagues [7, 8] found that gold in placers and dredging/sluicing tailings can be: visible (larger than 80 μm), fine (80–1 μm) and nano size (1000–1 nm). Modern electron microscopes with add-on X-ray spectrum analyzers allow reliable detection of gold particles down to 10 nm in size [9, 10]. The chemically bound disperse gold concentrators in placers are: sulfides and sulfate arsenides, quartz of certain generations, chalcedony, magnetite, hematite, nontronite, hydrogen oxides of Fe, Mn, etc. It is possible that these minerals–concentrators hold such atomic clusters and clusters of gold as: $(Fe,Au) – Au_2S_2$ Au_2SiO_2, Au_2SiO_4 and Au_nSi_m, which are metastable and may change from the cluster form to the atomic cluster form and backward: $(Fe,Au) – Au_2S_2 = (Fe,Au_3)S_2$. [4–5].

Methods of research

The proposed method of chemically bound gold detection was tested using different samples: oxidized ore, manmade minerals and placer sands. The feature of this method is the use of an active solution in preparing samples for crucible melting. This active solution contains chloride–hypochlorite compounds synthesized in photochemical treatment of a chloride–hypochlorite solution. At a certain pH, a chloride–hypochlorite compound generates hypochloric acid which, in the presence of ferrous iron, dissociates into hydroxyl radical, capable to penetrate the lattice of the mineral–concentrator of gold, and chloro anion:

$$HOCl + Fe^{2+} \rightarrow Fe^{3+} + OH^{\cdot} + Cl^{-}$$

When chemically bound gold interacts with such reaction particles, it forms complex anions of the type of $Au(OHCl)^{-}$ and $Au(Cl)_4^{-}$, for example, $[Au_2(OHCl)_2]nH_2O$. Crucible melting subjects complex anions to thermal dissociation, and the released cations of gold in the reducing environment of the melt are atomized and collected by lead and silver.

Actual information

The comprehensive research of the occurrence forms of gold in placers and their recoverability used the samples from Kruchina placer which is the largest gold source in Transbaikalia. **Table 1** describes the grade size distribution in sand and pebble of Tsentralny site of the placer deposit.

On the whole, the gold-bearing beds represent parallel 'stream lines' oriented coaxially to the river valley, 300–500 m in overall width, with partings with very low gold content. The steam lines hold rich gold areas of isometric shapes but slightly elongated along the axes. The content of gold varies in a very wide range of 0.46–17.78 g/m^3 (**Table 2**).

The authors implemented the nonstandard assaying of field samples of gold-bearing sand and washing tailings, which showed that the gold sand, rusty pelitic quarts and nontronitic clay at each site of the placer contained encapsulated and chemically bound disperse gold in commercial concentrations.

Lab-scale benchmark testing of in situ leaching

Leaching in percolation columns is assumed to be an adequate model of in situ leaching [11]. On the other hand, the lab-scale uranium leach tests carried out by geotechnical engineers at Navoi Combinat showed that in case of samples having nonuniform grain size composition, the

Table 1. Grade size distribution in sand and pebble at Tsentralny site of Kruchina gold placer

Size, mm	200–100	100–10	10–2	2–0.5	–0.5+0.0
Yield, %	18.3	23.2	24.9	21.6	12.0

Table 2. Gold distribution per size grades in rich areas of Kruchina placer

Size, mm	–2.0+1.0	–1.0+0.5	–0.5+0.25
Au content, %	0.2	14.4	85.4

vertical columns offered uneven wetting. For this reason, the new bench tester designed by us for simulation of in situ leaching consisted of tilted percolation columns (**Fig. 1**).

For the comparison of the stimulated and regular leaching results, the bench tester has 2 tubes: the lower check tube to feed a standard water solution of a reagent and the upper experimental tube, of the same size and capacity, to feed the activated solution treated in the above-arranged electrochemical reactor.

The test experiments showed that the flow chart with the standard water solution of sodium cyanide (1 g/l) to treat productive sand sample from Tsunkuruk site of Kruchina placer (sample weight 10 kg) at the constant pump delivery provided gold recovery of 23% to liquid phase. The treated sample of the same weight was preliminary soaked with photo-electro-activated carbonate–peroxide solution prepared in the laboratory reactor.

Results

The in situ leach flow chart with the stimulation cyanide solution (at concentration NaCN = 1 g/l) at the constant flow rate pumping ensured gold recovery of 78.7%. The leaching tests with hypochlorite–chloride solution in the diffusion–permeation and electrodiffusion modes were carried out on the lab scale and afield using large samples taken from the bottoms of dumps and tailings ponds (without separation of productive fraction). The gold recovery reached on the bench tester and afield was 82.3% and 73%, respectively.

For deep productive beds of Kruchina placer (occurrence depth greater than 5 m), for lean solid blocks of the placer and for manmade dumps, the in situ leach flow chart with flexible modes and parameters has been developed (**Fig. 2**).

In the proposed flow chart, the drainage trenches first cut along the lower boundary of a treatment block. From the bottom parts of the trenches, the horizontal transversal wells with a diameter of 250–350 mm are drilled at a spacing not less than 5–7 m. Then, the main vertical pump-in and pump-in/out wells are drilled and equipped. The double-duty wells are equipped with cylindrical solution distributors 700 mm long which are arranged on the casing pipes at the top of the productive bed. At the bottom of the productive bed, a liner filter 700 m long is set, with external pebble packing in the zone of local well expansion to 350–500 mm. The well drilling pattern design depends on economics and hydrodynamics. The drainage wells and the double-duty wells are used first for the preliminary drainage of local water for 3–10 days. Later on, water drainage is carried out in the drainage wells only. When drainage is terminated, the pump-in wells and the double-duty wells are used to feed the active high-concentration peroxide–carbonate solution prepared in a special photo-electrochemical reactor to the top and bottom portions of the productive bed until complete wetting (6–10%) of sands. The activation solution is prepared from a water solution of sodium hydrocarbonate by way of electrolysis, subsequent addition of certain amount of hydrogen peroxide and ultraviolet radiation of the resultant water-and-gas emulsion by a lamp with the wavelength of 182–252 nm (shortwave ultraviolet UV-C). The block saturated with the activated solution is aged for 3–7 days to allow for oxidation of sand minerals and to improve porosity of 'jackets'—ferrous oxides and hydroxides covering gold particles. After that, the bed is pumped in with the activated hypochlorite–chloride solution prepared in the photo-electrochemical reactor. The pregnant solutions are delivered to ground surface by air lift and are circulated through sorption columns. The mother solutions are re-fed, re-activated and fed again to the productive bed via the pump-in wells.

Fig. 1. In situ leaching bench tester

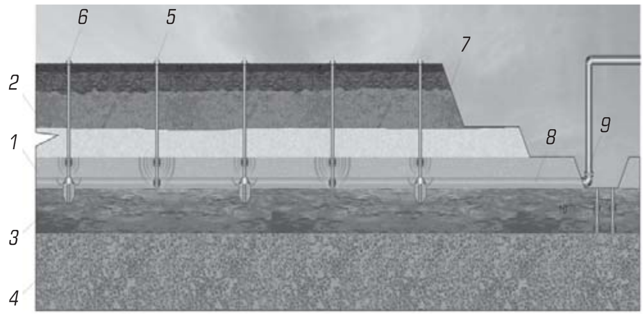

Fig. 2. Hydrodynamically adjustable in situ leach flow chart for placer gold

1 – Productive bed; *2* – Peat; *3* – Bedrock; *4* – Crystalline basement rock; *5* – Pump-in wells; *6* – Pump-out wells; *7* – Drainage trench; *8* – Drainage wells; *9* – Drain conduit; *10* – Observation and emergency wells

In the adverse hydrogeological conditions, when the pregnant solutions can intensively flow into the jointed or disintegrated bedrock, it is efficient to carry out in situ leaching in the electrodiffusion mode. The main leach solution containing a complexing agent and a gold oxidizer is fed several tens of hours after the feed of the primary hydrocarbonate–peroxide solution. In this case, the main solution components—hypochloric acid and its products—propagate by diffusion from the zone of initially high concentration to the production bed, react with gold and generate complex anions of the type of $Au(OHCl)^-$ and $Au(Cl)_4^-$.

At this stage, electrodes are placed in the wells: anodes in the pump-in wells and cathodes in the pump-out wells; the feed voltage is 8–12 V.

The leaching-generated complex gold anions periodically dissociate in the electric field into cations and anions. The cations of gold, before recombination with chlorine anions, displace toward the cathodes placed in the pump-out wells. Thus, ions of dissolved gold can move in the conditionally aqueous environment of the productive bed under the influence

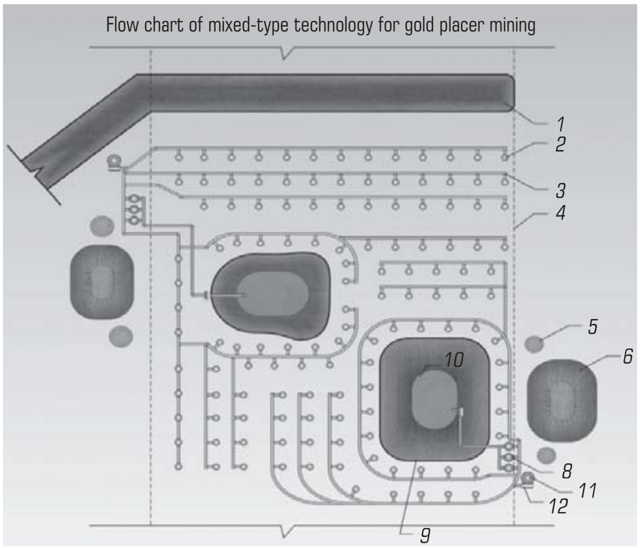

Fig. 3. Mixed-type technology of gold placer mining

1 – Drainage trench; *2* – Pump-in wells; *3* – Process solution feed pipeline; *4* – Placer boundary; *5* – Washing tailings; *6* – Dredging and sluicing tailings; *7* – Pump; *8* – Adsorption column; *9* – Pit; *10* – Containment pond; *11* – Reagent tank; *12* – Dosing pump

of the generated electric field from the anodes in the pump-in wells to the cathodes in the pump-out wells. Gold from the pregnant solutions is extracted by electric adsorption at ion-exchange resins placed in the cathode zones in the pump-out wells. The proposed method has been trialed in gold leaching from dredging and sluicing tailings at Kruchina placer: gold recovery reached 73% in 5 weeks.

This electrodiffusion in situ leaching technology was patented in Russia on 19 June 2012 [12].

The studies implemented a little bit later by our foreign colleagues led them to a conclusion that in situ leaching sometimes was an only economic method of mineral mining in the conditions of deep occurrence of minerals, large stripping and low content of a useful component [11, 13–15].

In placer sites with extremely nonuniform concentrations of gold and varied occurrence forms, it is expedient to combine in situ leaching and local digging of gold-bearing materials from coarse gold zones with washing of produced sand. The washing tailings can be then placed in the dug-out pits for the further re-leaching of gold fines and flakes (**Fig. 3**).

The technology runs as follows. Pits 9, after waterproofing of their sidewalls and bottoms, are filled with sludge from sluicing and jig washing machines, containing unrecovered gold fines and flakes, as well as with solid fraction of tailings from sand processing machines. Then, the water and solid mixture in the pits is subjected to decantation, and water is pumped out with simultaneous dosed addition of reagents. The resultant solution undergoes activation. Along placer boundaries 4, drainage trenches 1 are cut. In the solid blocks between the pits, pump-in wells 2 and 3 are drilled to feed the productive bed with the activated solutions. The pregnant solutions of in situ leaching, given their gold content is lower than the preset limit, are discharged to the pits through the drainage outlets in the sidewalls, and the mineral mass accumulated in the pits is wetted down to the slurry-like condition. The pregnant solutions are fed from the pits to the extraction columns, and the mother solutions liberated from gold are re-added with the reagents, re-activated and re-sent to in situ leaching.

Discussion

The authors have studied the grain size composition, gold content and mineralogical characteristics of production sites at Kruchina placer.

The lab-scale experiments and pilot trials of the technology of electrodiffusion and stage-wise (with pre-oxidation) in situ gold leaching using activated solutions (with subsequent electro-adsorption extraction of gold) from productive sand and from dredging and sluicing tailings at Kruchina placer have been carried out.

Conclusions

It is advisable to carry out gold placer mining using physicochemical geotechnologies with preliminary oxidation of gold-bearing sand before leaching with electro- and photo-activated solutions; in case of difficult hydrogeological conditions, it is expedient to use electro-diffusion leaching flow charts with preliminary drainage of deep placer sites.

Acknowledgements

The authors express their gratitude to Professors A. I. Trubachev, V. S. Salikhov, Yu. I. Rubtsov and Cand.Eng.Sci. Yu. S. Shevchenko from the Chita Division of the Institute of Mining, SB RAS, and to Cand.Eng. Sci. N. V. Zykov, Director of the Transbaikalia Mining College, for their help in the pilot trials of the electro-diffusion leaching technology. The studies were carried out using the scientific lab equipment and instruments of the Center for Processing and Storage of Scientific Data of the Far Eastern Branch of the Russian Academy of Sciences, supported by the Ministry of Science and Higher Education of Russia under Agreement No. 075-15-2021-663. The production research and chemical analyses were implemented at the Center of Mineralogical Research of the Khabarovsk Research Center, Far Eastern Branch of RAS.

References

1. Savichev A. A., Nevolko P. A., Kolpakov V. V. et al. Typomorphic features of placer gold from the Bystrinsky ore field with Fe-Cu-Au skarn and Mo-Cu-Au porphyry mineralization (Eastern Transbaikalia, Russia). *Ore Geology Reviews*. 2021. Vol. 129. 103948.
2. Takodjou Wambo J. D., Ganno S., Djonthu Lahe Y. S., et al. Geostatistical and GIS analysis of the spatial variability of alluvial gold content in Ngoura-Colomines area, Eastern Cameroon: Implications for the exploration of primary gold deposit. *Journal of African Earth Sciences*. 2018. Vol. 142. pp. 138–157.
3. Prokhorov K. V., Kopylov A. A. E. Promising ways to intensify the flotation process of copper-porphyry and gold-silver ores by applying electrochemical processing. *Problemy nedropolsovaniya*. 2020. No. 2 (25). pp. 96–106.
4. Bryukhovetskiy O. S., Sekisov A. G., Lavrov A. Yu., Rasskazova A. V. Improvement of development efficiency in multi-component refractory gold ore fields using in-situ leaching. *Gornyi Zhurnal*. 2020. No. 2. pp. 66–69. DOI: 10.17580/gzh.2020.02.09
5. Nenakhova E. V., Sakhno V. G., Kalashnikov Yu. D. et al. Self-assembling of nanodispersed forms of platinoids as a method of their extraction on the example of gold-silver ores of the Milogradovsky mining (Primorsky Region). *Proceedings of Voronezh State University. Series: Geology*. 2018. No. 4. pp. 103–106.
6. Oparin V. N., Smolyanitsky B. N., Sekisov A. G., Trubachev A. I., Salikhov V. S. et al. Promising mining technologies for gold placers in Transbaikalia. *Journal of Mining Science*. 2017. Vol. 53, No. 3. pp. 489–496.
7. Sekisov A. G., Lavrov A. Yu., Rasskazov A. V. Photochemical and electrochemical processes in geotechnology. Chita : ZabGU, 2019. 306 p.
6. Alves K. S., Sanchez S. B., Barreiro J. G., Palomares R. M., Compaña Prieto J. M. Morphological and compositional analysis of alluvial gold: The Fresnedoso gold placer (Spain). *Ore Geology Reviews*. 2020. Vol. 121. 103489.
7. Moiseenko V. G., Kuznetsova I. V. The role of gold, silver, and lead nanoparticles in the formation of deposits of precious metals. *Doklady Earth Sciences*. 2010. Vol. 430, No. 1. pp. 125–128.
8. Moiseenko V. G., Kuznetsova I. V. Nanogold in ancient limestone and dolomite of the Oktyabrskoe ore field (Priamurye). *Doklady Earth Sciences*. 2014. Vol. 456, No. 2. pp. 692–695.
9. Wang Y., Miller J. D. Current developments and applications of micro-CT for the 3D analysis of multiphase mineral systems in geometallurgy. *Earth-Science Reviews*. 2020. Vol. 211. 103406.

10. Zhou J., Gu Y. Geometallurgical characterization and automated mineralogy of gold ores. Gold Ore Processing. Adams. Amsterdam : Elsevier, 2016. pp. 95–112.
11. Martens E., Prommer H., Dai X., Sun J., Breuer P. et al. Electrokinetic in situ leaching of gold from intact ore. *Hydrometallurgy*. 2018. Vol. 178. pp. 124–136.
12. Sekisov A. G., Reznik Yu. N., Lavrov A. Yu., Shevchenko Yu. S., Zykov N. V. Method borehole cil from deep lying placers and man-made mineral formations. Patent RF, No. RU2504648 C1, Applied: 19.06.2012. Published: 20.01.2014. Bulletin No. 2
13. Martensa E., Zhang H., Prommera H., Greskowiakae J., Jeffrey M. et al. In situ recovery of gold: Column leaching experiments and reactive transport modeling. *Hydrometallurgy*. 2012. Vol. 125–126. pp. 16–23.
14. Martens E., Prommer H., Dai X., Wu M. Zh., Sun J. et al. Feasibility of electrokinetic in situ leaching of gold. *Hydrometallurgy*. 2018. Vol. 175. pp. 70–78.
15. Koch P.-H., Rosenkranz J. Sequential decision-making in mining and processing based on geometallurgical inputs. *Minerals Engineering*. 2020. Vol. 149. 106262. EM

UDC 622.276

V. V. POPLYGIN [1], *Associate Professor, Candidate of Engineering Sciences, poplygin@bk.ru*

[1] *Perm National Research Polytechnic University, Perm, Russia*

WELL PRODUCTION AFTER HYDRAULIC FRACTURING IN SANDSTONE ROCKS IN THE NORTH OF THE PERM REGION

Hydraulic fracturing is one of the most popular ways of increasing well production. The article investigates the results of hydraulic fracturing (HF) in sandstones of the northern Perm region territory (Tula–Bobrikovian oil reservoirs of the Visean stage). The oil of these sites has a high and medium gas content, and the rocks have a wide range of permeability values as well as natural cracking. Based on the value of the linear Spearman correlation coefficient, the most significant parameters affecting the efficiency of the HF are determined. A ranking of these parameters has been performed. The greatest influence on well productivity after HF is the bottomhole pressure and productivity indices before HF. The relationships between the geometrical dimensions of HF cracks and the volume of the injected proppant are shown. The dependencies of well parameters after HF on well parameters before HF are constructed. The permeability coefficients of the reservoir remote zone do not actually change much after HF and the permeability coefficients of the bottom-hole zone increase on average by 30%. The impact of the formation and bottomhole pressure values on productivity indices after HF has been noted. At the same time, the rate of oil production decrease after HF is also dependent on bottomhole pressures. Recommendations have been made on the selection of wells for HF at the site under study and similar production targets as well as their post-operation technology practices. Changes in well production after HF are forecasted depending on geological and technological parameters.

Keywords: *Oil reservoir, hydraulic fracturing, productivity index, bottom-hole pressure, deformations*

DOI: *10.17580/em.2022.02.09*

Introduction

Currently, there has been an increase in the proportion of hard-to-recover oil reserves, including highly viscous oils, low permeability reservoirs, etc. To increase oil production, geological and technical measures are being actively implemented at such deposits: hydraulic fracturing, acid treatment, radial drilling, etc. Hydraulic fracturing is one of the most efficient and common methods of increasing well productivity. The use of HF improves the hydrodynamic connection of wells with the productive formation and contributes to the fuller development of oil reserves [1]. The selection of wells for the HF requires the analysis of information on the history of the well operation, past activities, the well technical state, and its bottom-hole zone, etc. [2]. The main factors affecting the hydraulic fracturing efficiency are [3–8]:

- geological parameters of the formation: effective oil-saturated thickness, permeability, porosity, pressure, etc.;
- fluid properties: viscosity and density;
- technological parameters of HF: opening and half-length of cracks, the mass of proppant, etc.

Researchers note the effectiveness of HF in different deposit conditions, including low permeability reservoirs [9–10]. In some fields, the energy state of the production targets has a significant impact on the well productivity incremental growth after HF [11, 12]. Formation conditions influence the choice of process fluids and materials [13–15], and injection technology conditions on the geometry of cracks [16]. The developed natural cracking [17, 18] and high perforation density [19] increase the HF efficiency. The reduction of reservoir pressures relative to the initial values may lead to irreversible deformations of the reservoir and a reduction in pore space permeability. In the design of the work, special attention should be paid to deposits with a high content of oil-soluble gas and bottomhole pressures lower than the saturation pressure.

Laboratory and field stress research, well geophysical research, fracture development monitoring, and research of fracture fluid rheological parameters are essential for successful HF design, as well as core filtration testing [20, 21].

Analysis of hydraulic fracturing results

The article studies sandstone of oil fields in the North of Perm region (Tula–Bobrikovian oil reservoirs of the Visean stage) (**Fig. 1**).

Ranges of physical and geological characteristics

Depth	1919–2340 m
Reservoir thickness	3.1–11.6 m
Porosity	0.12–0.18 unit fraction
Permeability	79–653 $\mu m^2 10^{-3}$
Reservoir oil density	730–839 kg/m^3
Dynamic viscosity of reservoir oil	1.22–3.19 mPa·s
Gas content	64.2–164.6 m^3/t
Saturation pressure	11.56–16.0 MPa
Initial reservoir pressure	20.3–24.4 MPa