Arsenic in refractory gold ore processing

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ABSTRACT

With "easy" ores becoming diminished, extractive industries are now shifting towards difficult deposits. In the future, gold-arsenic-bearing refractory ores will represent a prime example of the type of ores that may become more typical sourse for global gold recovery operations. Mining and beneficiation of As-bearing ores inevitably produce As-bearing wastes, which exacerbate any natural As mobilization. The mobility of As is governed by the interplay of redox reactions, adsorption/desorption, ion exchange, precipitation/dissolution, and biotransformation. The dominant processes depend on local biogeochemical conditions of the media, such as pH, Eh, chemical composition, as well as the presence and intensity of biological activity. This article provides an overview of current research on arsenic contamination of the environment caused by mineralization, mining and extraction of gold on the example of specific gold deposits.

Keywords: refractory gold-bearing ores, arsenopyrite, gold recovery, arsenic, mobility.

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Introduction

Historically, gold is a symbol of prosperity. Nowadays, gold is one of the major economic assets of nation states, and a significant means of international payment. About 60% of all the mined gold worldwide is in the hold of governments and central banks, therefore gold mining is one of the strategic motors of the economy [1].

The common causes for refractoriness in ores are physical or chemical binding of the gold and the presence of reactive gangue minerals. Over the past century, many methods have been developed to increase gold recovery rates and itensify gold leaching [2-4].

However, the main concern in mining and processing of the refractory As-bearing gold ores is As. The concentration of As in gold ores can vary from trace levels to more than 5000 mg/kg. Such gold is not extractable without significant ecological contamination from the associate arsenopyrite mineralisation. Arsenic poses economical risks by complicating the gold recovery process and affecting gold production costs, as well as creating ecological risks associated with emission and disposal of As-containing wastes.

A number of papers have been published that attempt to elucidate sources or triggers of As in natural environments and industrially-contaminated areas, mechanisms of its attenuation, and controls. Here, we present an overview of current research and observations on arsenic contamination caused by gold mineralisation, mining, and extraction. We will do so by reviewing the case studies of particular mines.

Mokrsko-West gold deposit

The Mokrsko-West gold deposit (MWD) in the Czech Republic, containing an estimated 100 t of gold reserve [5], is a unique example of As contamination caused by a gold deposit which is unaffected by mining. The main constituents of the MWD ore are quartz, calcite, and silicate minerals. The main As-containing mineral is gold-bearing arsenopyrite, which is responsible for 95% of the As load into local soil. The remaining As input comes from loellingite, stibnite, and pyrite. Soils are generally pH neutral, but slightly lower pH in the
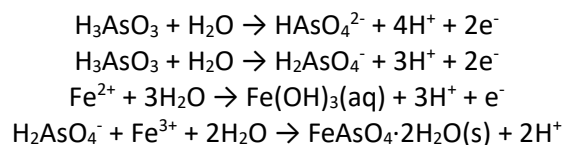
surface layers, due to presence of organic acids. The average precipitation in the region is 555 mm/year, with mean temperatures in July of 17°C, and -3 ^{o}C in January. Weathering of primary minerals generates secondary As-bearing minerals, such as arseniosiderite, ferrihydrite, goethite, hematite, pharmacosiderite, and scorodite. The concentrations of As in the soils have reached >200mg/kg nearby (at a distance of 1.12 km). As is found as arsenates and Fe oxyhydroxides (goethite and hematite) in soils, whereas in sediments As is associated mainly with Fe oxyhydroxides. The As content in the groundwater varies from 255 - 1690 µg/L, and around 50 - 340 µg/L in surface water. Waters are neutral to slightly alkaline, of Ca-HCO$_3^-$ type. High As concentrations were detected in in the redox transition zone of groundwaters, as a result of the reductive dissolution of scorodite, arseniosiderite, pharmacosiderite, and As-rich iron oxyhydroxides. Reducing conditions can occur due to groundwater elevation or/and intense microbial activity. In surface water, the highest As^{3+}/As^{5+} ratio (>16) was detected in muddy areas rich in organic matter. A positive correlation between As^{3+}/As^{5+} and DOC, recorded in all water samples, points to the important role of microbial processes in controlling the speciation and mobility of arsenic at the MWD.

Arsenic transformations occurring at the MWD site start from arsenopyrite oxidation in the environmentally-relevant pH range of 4-9, and the release of As^{3+} and Fe^{2+}:
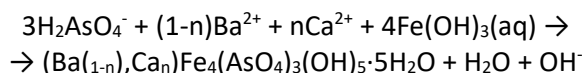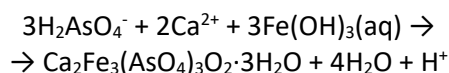
$$FeAsS + 7H_2O \rightarrow Fe^{2+}(aq) + H_3AsO_3(aq) + 11H^+ + 11e^- + SO_4^{2-}$$
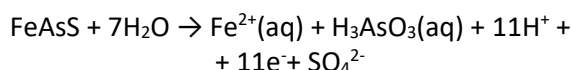
If dissolved As^{3+} is transported to a more reducing environment, such as sediments or shallow subsurface soils with elevated groundwater levels and high microbial activity, the main mechanism of As immobilisation is bonding to newly formed Fe and As sulfides by adsorption and co-precipitation. However, the most probable sequestering mineral is Fe sulfide, as the concentration of dissolved As^{3+} does not exceed the solubility of realgar and orpiment in the reducing sediments of MWD. This hypothesis is supported by the fact that, firstly, As sulfides can be formed at low pH, in reducing conditions, and at low Fe^{2+} concentrations. Secondly, thermodynamic calculations show that during the slow decrease of redox potential, Fe sulfides (pyrite and mackinawite) tend to oversaturate earlier than As^{3+} sulfides. Hence, the main control on As transport in reducing environments is the solubility of Fe sulfides.
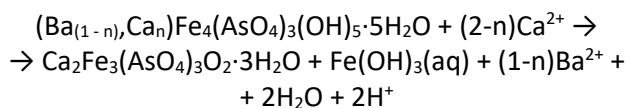
In contrast, under oxidising conditions As^{3+} oxidises to As^{5+}, and Fe^{2+} to Fe^{3+}. Below pH 3 in the oxidising zone of saprolite, high concentrations of As^{5+} may result in the formation of scorodite:

$$H_3AsO_3 + H_2O \rightarrow HAsO_4^{2-} + 4H^+ + 2e^-$$
$$H_3AsO_3 + H_2O \rightarrow H_2AsO_4^- + 3H^+ + 2e^-$$
$$Fe^{2+} + 3H_2O \rightarrow Fe(OH)_3(aq) + 3H^+ + e^-$$
$$H_2AsO_4^- + Fe^{3+} + 2H_2O \rightarrow FeAsO_4 \cdot 2H_2O(s) + 2H^+$$

Dissolution of carbonate minerals releases Ca^{2+} and Ba^{2+} into solution, thus neutralising acidity. At circumneutral pH, arseniosiderite and Ba-pharmacosiderite can be formed from such alkaline earth cations.

$$3H_2AsO_4^- + 2Ca^{2+} + 3Fe(OH)_3(aq) \rightarrow$$
$$\rightarrow Ca_2Fe_3(AsO_4)_3O_2 \cdot 3H_2O + 4H_2O + H^+$$

$$3H_2AsO_4^- + (1-n)Ba^{2+} + nCa^{2+} + 4Fe(OH)_3(aq) \rightarrow$$
$$\rightarrow (Ba_{(1-n)},Ca_n)Fe_4(AsO_4)_3(OH)_5 \cdot 5H_2O + H_2O + OH^-$$

Incongruent dissolution of Ba-pharmacosiderite can result in arseniosiderite:

$$(Ba_{(1-n)},Ca_n)Fe_4(AsO_4)_3(OH)_5 \cdot 5H_2O + (2-n)Ca^{2+} \rightarrow$$
$$\rightarrow Ca_2Fe_3(AsO_4)_3O_2 \cdot 3H_2O + Fe(OH)_3(aq) + (1-n)Ba^{2+} + 2H_2O + 2H^+$$

Hence, in oxidising environments, As mobility is controlled by the solubility of arsenate minerals, as well as the degree of As adsorption onto Fe oxyhydroxides. The latter is the most important sink of As at the MWD, in some cases containing up to 16% As.

In the transition zone (the upper boundary of which lies just below groundwater level), the rate of sulfate reduction into sulfide is low, and the concentration of dissolved As is insufficient to induce As sulfide precipitation. Under these redox conditions, arsenates are relatively insoluble, however, in the presence of reductants, the concentration of arsenates may be substantially greater. It has been found, by sequential extraction, that As is mostly bound to a reducible fraction, confirming that the high As content is a result of reductive dissolution of arsenates and Fe oxyhydroxides.

Iron Quadrangle

Another example is The Iron Quadrangle (IQ) in Brazil. This is associated with a large As geochemical anomaly arising from gold mineralization and

amplified by gold mining operations [6]. Overall, 390 000 t of As has been discharged into the drainage system of the IQ region. The regional climate is temperate and tropical, sub-humid, with dry winters (April - October), in spite of a mean annual precipitation of 1500-1900 mm. Rain falls from November to January. High average temperatures and high precipitation induce intense weathering of sulfides, and this might be expected to result in AMD. However, the presence of carbonates in the ore neutralizes the waters, produced from sulfide mineral oxidation and dissolution, yielding pH > 7.5. The Eh of water is in the range of 128-220 mV.

High As in the groundwater of the IQ resulted from leaching of arsenopyrite oxidation products by fluctuations in the water table. Water running from a mineralised vein from the Passagem mine contained 2980 µg/L As, for example [6]. The As content in water from an adit reached 800 µg/L. This water flows to the Carmo river, where the concentration of As in sediment samples close to the Passagem mine is found to be 4700 mg/kg. The concentration of As in water is found to be lower in winter. This is explained by less pronounced dilution in winter, and subsequent low water flow, allowing deposition of As-containing fine-grained material. Common minerals identified in the sediments are quartz, goethite, hematite, kaolinite, and illite. Sequential extraction demonstrates that the As is mostly bound to the iron oxyhydroxide fraction (goethite, hematite). Up to 300 µg/L As is detected in surface water samples.

The speciation of dissolved As shows the presence of As^{3+} in water samples, contradicting the results of speciation calculations obtained by the PHREEQC geochemical code. This might be due to the slow kinetics of redox reactions, meaning that waters have not reached chemical equilibrium, or that As^{5+} has been sequestered by some solid phases. Oxidation of the primary ore leads to the formation of iron oxides and hydroxides as well as As^{5+} and As^{3+} oxyanions. As^{5+} may be partially consumed by precipitation of scorodite (together with Fe^{3+}) under oxidizing conditions and pH<4 [7], and selective adsorption onto clay minerals and goethite compared to As^{3+}. This may be an explanation for the presence of As^{3+}, which contradicts PHREEQC speciation calculations. Precipitation of scorodite and goethite with up to 8% As has been observed in Passagem and Ouro Preto mines. At the Raposos gold deposit, As concentrations reached more than 10000 mg/kg in Fe-rich material. However, where the abundance of

carbonates promotes pH to rise above 4, incongruent dissolution of scorodite occurs with the formation of goethite, Fe-oxyhydroxide, and $H_2AsO_4^-$ oxyanions, as well as possible As desorption from goethite and other Fe and Mn oxyhydroxides. TCLP-like tests resulted in leaching of 1-4 wt. % As (2-196 mg/kg) from river sediments and sediment from waste tailing. Other sources of As are ancient and modern tailings, containing As in the form of arsenolite, As-bearing Fe-oxihydroxides, and amorphous iron arsenates. To summarize, two mechanisms of arsenic control have been identified in the IQ gold mining region: precipitation of scorodite and goethite, and adsorption of arsenic onto iron oxides and hydroxides.

Salanfe gold mine

The former As-bearing Salanfe gold mine, situated in Western Switzerland, is another example of arsenic contamination accelerated by mining operations [8]. 700 t of As has been discharged during the mining operations at the Salanfe. Waters above the mine area contained about 5 µg/L background As. Despite the low gold production (only 55 kg), it has left behind dumps with elevated As content reaching up to 10 wt.%, and soils containing from 50 mg/kg to several wt.% of As. In the oxidising pH 8 waters percolating the mine and dump ($Ca-Mg-HCO_3-SO_4$-type), As concentrations varied in the range 60-4000 µg/L. This is explained by the mobility of As in alkaline conditions, induced by dissolution of carbonates. However, the concentration of As gradually decreases with distance from the mine adits and heap wastes, reaching 100-160 µg/L in Lake Ottan located 200 m below the mine, though the type of water remained the same. Primary (arsenopyrite, loellingite, pyrite, hematite) as well as secondary As-containing minerals (goethite and amorphous iron oxyhydroxides) were found in fine-grained waste materials. Soil samples contained As in iron oxyhydroxide and Al-bearing fractions. The organic fraction appears to play an insignificant role in the retention of As, due to thin soil cover of less than 10 cm, and very rare reducing conditions. The climate of the region is relatively dry, continental, with a mean temperature of 3°C. The release of As resulted from weathering of exposed mine waste, and downhill creep of As-rich waters. Attenuation of As was more pronounced in sediments and soils, than in downstream water. This was attributed to the desorption of As from Al- and Fe-oxyhydroxides,

associated with the alkaline pH of waters resulting from carbonate buffering. As attenuation in water here results from dilution and circulation of surface and ground waters.

Lucky Shot Gold Mine

A further example is provided by Lucky Shot Gold Mine, one of thousands of abandoned sites of historical mining in Alaska, which produced nearly 7 t of gold. The primary source of As is mine adits, although tailing piles also make a contribution to the As load [9]. Surface and mine waters are of Ca-HCO$_3^-$ -type, circumneutral to mildly alkaline due to carbonate buffering, and well oxygenated. The water from the adits contains 700 µg/L dissolved As (differing <2% between filtered and unfiltered samples), almost entirely in trivalent form. The deviation from thermodynamic prediction has been attributed to the short residence time of As in the water, so As^{3+} does not completely transform to As^{5+}. Downstream, rapid dilution lowers the As concentration (below 2 µg/L) as well as the As^{3+} proportion due to progressive oxidation.

The environmental impacts of both Lucky Shot and Salanfe Gold Mines are not significant, since the contaminated areas are limited in each case. It has been concluded that these mines do not pose a threat to local community health, although future mining may have impacts on the environment at the Lucky Shot Gold Mine.

East Otago Gold Mines

Moving to New Zealand, the primary source of As at the East Otago Gold Mines is arsenopyrite [10]. The annual precipitation in the area is 400-800 mm with a similar amount of evaporation. Abandoned mines show accelerated weathering of arsenopyrite, forming scorodite and pharmacosiderite in the oxidised zones. Waters from old mines have a pH around 6-7 with up to 4 ppm As, whilst the background concentration of As is 0.01 ppm. The concentration of As in pH 5 slurry of degraded old tailings reaches 33,000 ppm, mainly in the form of scorodite. The content of dissolved As is determined to be 0.75 ppm. This suggests that, in the old tailings, As release is controlled by scorodite precipitation.

At the active mining site, Macraes, pH 10 waters contain over 200 ppm As, which is explained by the low solubility of scorodite at this pH. The average As content of soil samples is around 200 ppm, whereas primary veins contain up to 10,000 ppm As.

Attenuation of As in soil is mainly mediated by adsorption onto iron oxyhydroxides and phyllosilicate minerals, and local temporary immobilisation by precipitation of scorodite. The As concentration in water is controlled by downstream dilution and by precipitation of scorodite in low pH waters.

Reefton gold field deposits

Mining and processing of As-containing gold ores in the Reefton gold field deposits (New Zealand) has also led to high As concentrations across the mine sites. Globe Progress Mine, Blackwater Mine, and Snowy River Battery Site have been studied to elucidate mechanisms of As dispersion and control [11]. The Blackwater ore contained mostly arsenopyrite with rare pyrite, whereas at Globe Progress Mine pyrite predominated over arsenopyrite. The principal source of As in Blackwater Mine is the Prohibition Mill Site, where roasting was employed to process the arsenopyrite-rich ore. This generated large amounts of arsenolite, crystals of which still can be found in the condenser tower of the roaster as well as in the surrounding area. Annual precipitation in the region is 2,300 mm, and the mean temperature is 12 °C. Site run-off is concentrated in a wetland, where As concentrations as high as 52 mg/L are detected in a Ca-AsO$_4$-type water as a result of arsenolite solubilisation. Oxidation of arsenites lowers the pH of wetland water to 4-5. The wetland water then percolates to a man-made dam with abundant exposed carbonate rocks, neutralising acidity to circumneutral pH. This dramatically decreases the As content to 2.4 mg/L.

Further downstream, attenuation of As in water, emanating from the dam, is a result of pure dilution by tributaries. 14 km from the Prohibition Mill site, Blackwater River still contains 0.003 mg/L As. Although it is well below the maximum contaminant level of As (MCL is the maximum concentration of a chemical that is allowed in public drinking water systems), this means that survival of 99% of aqueous species cannot be guaranteed according to ANZECC (2000) guidelines [12].

The point sources of As at the Snowy River Battery Site are a roaster system and a historic adit. Circumneutral run-off from the mine site flows into the Snowy River. Discharge from the adit inflows to the Snowy River 150 m upstream of the site. In contrast to the Prohibition Mill Site (with residues containing up to 40 wt.% As), all arsenolite has dissolved at the Snowy River Battery Site. The concentration of As at the Snowy River Battery Site

substrate is lower, 26 wt.%. Scorodite has been suggested to control the As concentration, since scorodite's solubility is two (at pH7) to five (at pH 4) orders of magnitude lower than that of arsenolite.

The Globe Progress Mine was functional from 1870 up to 1920, and reopened for mining in 2007. Arsenic is distributed to the environment through oxidation of arsenopyrite and As-bearing pyrite (up to 1 wt.% As). At the adit entrances, As is sequestered as a 4 cm thick layer of hydrous ferric oxides with up to 20 wt.% As, whilst the As content in discharge from the adits reached 59 mg/L. However, where discharge water joins a local creek the As concentration gradually decreases due mixing.

Arsenic chemistry in these mine sites has been determined by roasting technology and gas handling systems. Dissolution and oxidation of roaster-derived arsenolite resulted in high localised As^{5+} concentrations in discharged waters. Three mechanisms of As attenuation have been proposed by Haffert and Craw [9]: 1) precipitation of scorodite, 2) chemisorption to hydrous ferric oxides, and 3) downstream dilution with local catchment water.

In oxidising and acidic conditions, such as that at Prohibition site, scorodite precipitation occurrs. Owing to substantial carbonate alteration at the Snowy River Site, dolomite and ankerite dissolve, thus increasing pH to circumneutral values according to the reactions:

$$CaMg(CO_3)_2 + 2H^+ = Ca^{2+} + Mg^{2+} + 2HCO_3^-$$
$$FeMg(CO_3)_2 + 1/4 O_2 + 5/2H_2O = Fe(OH)_3 + Mg^{2+} + 2HCO_3^-$$
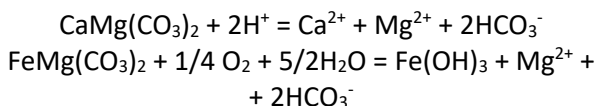
In the non-pyritic ore of Blackwater, Fe from ankerite dissolution precipitates as hydrous ferric oxide (HFO), due to low solubility of Fe at circumneutral pH. When the amount of HFO is insufficient for As sequestration, As may persist at high concentrations, exceeding MCL, for up to 10 km downstream, until diluted by regional tributaries. The effectiveness of dilution depends on catchment morphology. In pyrite-rich mine sites, HFO is mainly generated by oxidation of pyrite:

$$FeS_2 + 15/4O_2 + 7/2H_2O + 4HCO_3^- = Fe(OH)_3 + 2SO_4^{2-} + 4H_2CO_3$$
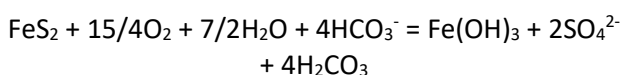
Naturally formed HFO has high reactivity and surface area, and so immobilises dissolved As through chemisorption (adsorption, surface complexation, co-precipitation, and ion exchange). It has been concluded that there is no need for anthropogenic rehabilitation, and that the aforementioned natural mechanisms of As attenuation are sufficient to improve the quality of downstream water [11].

Giant Mine

Perhaps the most severe example of the adverse environmental impact of refractory gold mining and processing is the legacy of As contamination at Giant Mine in Canada, with a remediation cost of about 1 billion Canadian dollars [13]. Though full implementation of the remediation plan (designed for perpetuity) at Giant Mine will reduce As discharge to the environment from 900 to 610 kg/year, it will not be able to completely eliminate the As load.

After 50 years of prosperous gold mining by private companies the Giant Mine is now abandoned, and environmental liability belongs to the federal government and taxpayers. In the gold ore, arsenopyrite and pyrite accounted for 95% of the sulfides. The processing technology comprised ore roasting and cyanidation. During roasting, most of the arsenopyrite oxidised to As_2O_3, maghemite (predominantly γ- Fe_2O_3 [14]) and hematite.

The point sources of As at Giant Mine are roaster-derived As_2O_3, which was aerially distributed and deposited in surface soil pockets across the mine site, As_2O_3 baghouse dust stored in underground chambers, and several mine tailings. Untill the proper implementation of emission control in 1963, some 20,000 t of As_2O_3 (which is nearly 86% of all the As_2O_3 produced during the entire roasting operations) had been discharged into the air. Despite high solubility, particles of As_2O_3 have been found, unaffected, in soil downwind of the roaster. Scorodite rims have been observed on some As_2O_3 particles, which may have formed after the contact with acidic Fe-bearing solutions.

The total As concentration in soil samples reaches up to 5,760 mg/kg. By comparing Au, As, and Sb proportions in the soil and in the condensed historic dust, it has been suggested that most of the soil As was likely deposited before the emission control [15]. 237,000 t of As_2O_3 baghouse dust is still kept in underground chambers. Neutral seepage, collected from drill holes and fractures near the underground chambers, contains as much as 4,000 mg/L As, mostly in the trivalent form (70%) [16].

The As content in tailings fluctuates in the range of 1000-5000mg/kg. The high As concentration is a result of circumneutral pH conditions, bufferred by carbonate-rich mineralogy, and the processing conditions. Due to the relatively low temperature of

roasting (500ºC), carbonates remain unaffected and prevail in tailings over sulfides, precluding acid drainage. Weathering of tailings induced oxidation of unroasted remnant sulfide minerals, in the form of Fe oxyhydroxide rims on pyrite and arsenopyrite grains [14]. Aeolian and aqueous transport of tailings still poses a risk to human health. *In vitro* bioaccessibility tests of soil samples have shown that 40% of the As may be bioaccessible if ingested and 20% of the As would be bioaccessibile if inhaled.

Discussion

The environmental impacts of operational and former gold mine sites is mainly associated with voluminous waste rocks and mine tailings. Tailings completely change landscape and topography, affect the quality of surface and groundwater.

One solution would be industrial use of tailings as bricks and tiles. However, despite their potential technical feasibility, most studies on the possible use of gold mill tailings have been proven to be futile or economically unviable [17]. The mineralogy of tailings is complex, depending on ore composition, the method of generation (ore beneficiation or metallurgical processing), climate, and maintenance conditions. In semi arid climates, inappropriately maintained tailings (uncovered, dried ponds) release fine particles into the air due to evaporation and wind erosion, thus posing risks of inhalation and incidental ingestion to local community.

Since As toxicity varies with oxidation state and chemical form, mine tailings certainly demand accurate determination of As speciation. Typical secondary minerals in mine wastes are in low abundance, microcrystalline, or nearly amorphous, often demanding identification at the micro- or even nanoscale, potentially using novel synchrotron-based techniques.

Studies demonstrate that at most mine sites, HFO phases play a crucial role in sequestering As via adsorption or co-precipitation [18]. Other mineral phases are also capable of immobilizing As, depending on the pH of media. At pH <2.5 As may substitute for sulphate in the crystal structure of jarosite $KFe_3(SO_4)_2(OH)_6$ [16], while at higher pH ranges of 2.5-6, As can be adsorbed onto schwertmannite $Fe_8O_8(OH)_6SO_4$ [19].

Scorodite is rarely found [20], probably due to the low Fe content and neutral pH in some tailings.

Post-disposal variations in pH and Eh of mine tailings can change As speciation, compromising As stability and altering As partitioning between liquid and solid phases. Sometimes it is necessary to maintain certain Eh-pH conditions, which favour retention of particular As-bearing species.

For instance, mine tailings at the Giant Mine, mainly consisting of roaster-derived iron oxides, demand the maintenance of oxidising conditions to avoid reductive dissolution or desorption of As [16]. In sulfide-rich mill tailings, liming is often used as a common measure to reduce the acid-generating potential of wastes. However, liming may be inappropriate if the risk of exposure to As via inhalation of tailings' particles is high, as iron arsenates are altered to calcium-iron arsenates, which are highly bioaccessible in neutral pH fluids [21].

Conclusion

In summary, several factors control As flux into environment in refractory gold mining and extraction. Factors such as climate, hydrographic network, and ore mineralogy are beyond the control of miners.

The key human factor, controlling the negative impact of gold recovery from double refractory Au-As-bearing ores, is a choice of the optimal (ideally economically efficient and eco-friendly) method for gold extraction, that takes into account both ore mineralogy, and further safe disposal of As-bearing wastes in compliance with local environmental standards.

Tests of site-specific As speciation, combined with bioaccessibility are crucial in making such an important choice. Ultimately, this site-specific As knowledge will enable prioritisation of historical mine residues for better management and remediation, to predict the risks associated with exposure to As in future, thus to best understand how to eliminate or diminish As bioaccessibility for humans, and ultimately the environmental impact of gold mining in general.

Conflicts of interest. The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Қиын өңделетін алтынды кендерді өңдеуде қоршаған ортаның мышьякпен ластануы

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ТҮЙІНДЕМЕ

Бай және жеңіл өңделетін кендердің қоры азайған сайын, алтын өндіру саласы кедей және өңделуі қиын кен орындарына көп көңіл бөлуде. Келешекте алтын-мышьякты қиын өңделетін кендер жаһандық алтын өндіру саласында қолданылатын әдеттегі кен түрі болатыны анық. Құрамында мышьяк бар алтынды кендерді өндіру және байыту сөзсіз мышьякты қалдықтардың түзілуіне әкеледі, бұл мышьяктың табиғи қозғалғыштығын одан сайын арттырады. Мышьяк қозғалғыштығы бірнеше факторлардың өзара әрекеттесуімен анықталады, олар: тотығу-тотықсыздану реакциялары, адсорбция/десорбция, иондық алмасу, тұнбаға түсу/еру және биотрансформация процестері. Басымдыққа ие процестер - pH, Eh, химиялық құрам, сонымен қатар биологиялық белсенділіктің болуы мен қарқындылығы сияқты жергілікті биогеохимиялық орта жағдайларына тәуелді. Бұл мақалада нақты алтынды кен орындарының мысалында қиын өңделетін алтынды кендерді өндіру және қайта өңдеу барысында түзілетін мышьяктың қоршаған ортаны ластауы бойынша қазіргі заманғы зерттеулерге шолу жасалды.

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Загрязнение окружающей среды мышьяком при переработке упорных золотосодержащих руд

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АННОТАЦИЯ

С истощением запасов богатых и легкоперерабатываемых руд, золотодобывающая отрасль все больше переходит к разработке месторождений бедных и упорных руд. В будущем золото-мышьяксодержащие упорные руды будут представлять собой яркий пример типичных руд, используемых для извлечения золота. Добыча и обогащение мышьяксодержащих руд неизбежно приводит к образованию мышьяксодержащих отходов, которые усугубляют процесс естественной мобилизации мышьяка. Подвижность мышьяка определяется взаимодействием нескольких факторов: окислительно-восстановительных реакций, процессами адсорбции/десорбции, ионного обмена, осаждения/растворения и биотрансформации. Доминирующие процессы зависят от локальных биогеохимических условий среды, таких как pH, Eh, химический состав, а также наличие и интенсивность биологической активности. В данной статье представлен обзор современных исследований и наблюдений по загрязнению мышьяком окружающей среды, вызванном минерализацией, добычей и извлечением золота на примере конкретных золотосодержащих месторождений.

Ключевые слова: упорные золотосодержащие руды, арсенопирит, извлечение золота, мышьяк, мобильность.

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