



Release of arsenic from cyanidation tailings



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ABSTRACT

At a gold mine in northern Sweden, gold occurring as inclusions in pyrrhotite and arsenopyrite is leached by cyanidation of the ore. The main sulphide minerals in the ore are pyrrhotite and arsenopyrite. Effluents from the cyanidation process are treated with $\text{Fe}_2(\text{SO}_4)_3$ to form Fe-precipitates suitable for the co-precipitation of As. The aim of this study was to perform static and kinetic leaching tests on the ore and tailings to define geochemical processes governing As mobility. Sequential leaching tests suggested that the majority of dissolved As deriving from the sulphide fraction in the ore was incorporated in newly formed Fe-precipitates in the tailings. The mobility of As in the tailings was therefore mainly dependent on the stability of these As-bearing Fe-precipitates. Weathering cell tests (WCT) involving 31 weekly cycles of wetting and air exposure were conducted to assess the stability of the As in the tailings under accelerated weathering conditions. The first stage of the WCT was characterized by a $\text{pH} \approx 5$ and low As leaching, probably driven by the dissolution of amorphous Fe-As species. In the second stage of the WCT, leaching of Fe, S and As increased and the pH decreased to <3.5 . An increase of the leachate's molar Fe/S-ratio suggested that pyrrhotite oxidation was occurring. The falling pH destabilized As-bearing Fe-precipitates, causing further As release. The total As release during the WCT corresponded to only a small proportion of the tailings' total As content. The accelerated As-leaching observed towards the end of the WCT could thus indicate that its release could increase progressively over time.

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1. Introduction

Gold can occur in its native form (free gold) or may be encapsulated in other minerals (e.g. pyrite, quartz, arsenopyrite, loellingite, etc.). Gold particles are usually separated by gravity or recovered by leaching the ore using a cyanide solution. During the cyanidation process, the ore is subjected to a cyanide solution under alkaline conditions (pH 9.5–10) for up to 36 h. Many gold ores contain arsenic (As) in the form of arsenopyrite, which usually co-exists with other sulphide minerals, such as pyrrhotite and pyrite. Tailings from sulphide ore mines are often chemically reactive due to their content of Fe-sulphide minerals, such as pyrite and pyrrhotite. The weathering of Fe-sulphide minerals can be a strongly acidifying process and is considered to be the main cause of acid mine drainage (AMD) (INAP, 2009). Arsenic does not form stable complexes with cyanide like Au, but it is very soluble under the alkaline conditions used during cyanidation. Therefore, the water used in this process must be treated to remove dissolved arsenic before it can be discharged into tailings facilities. The

management of As-rich tailings generated by gold extraction processes generally focuses on the stability of secondary As-phases because As-sulphides are assumed to be oxidized during gold extraction (Paktunc et al., 2004). The main secondary As minerals present in tailings after cyanide leaching are believed to be arsenates (Craw et al., 2003). Under oxidizing conditions, arsenates form complexes with metals such as Fe, Al and Ca. The stability of these metal arsenates depends on several factors, including the pH , metal/As ratio, redox conditions, availability of O_2 and CO_2 and the presence of anions, such as SO_4^{2-} , that compete with arsenates for sorption surfaces. Iron and Al-arsenates are dominant phases in acidic environments and are less soluble than Ca-arsenates, which predominate in calcareous tailings (Williams et al., 1996). Arsenate may precipitate as scorodite, $\text{FeAsO}_4 \cdot 2\text{H}_2\text{O}$ (Paktunc et al., 2008), or poorly-crystalline Fe(III)-arsenates (Le Berre et al., 2007; Parviainen et al., 2012). Alternatively, it may co-precipitate as Ca-Fe-arsenates (Pantuzzo et al., 2008), sorb to amorphous Fe-oxy-hydroxide phases (Korte and Fernando, 1991) or substitute for sulphate in jarosite (Paktunc and Dutrizac, 2003).

Gold mine tailings slurries from As-enriched sulphide ores are often treated with lime and $\text{Fe}_2(\text{SO}_4)_3$ to promote the formation of stable Fe-As-precipitates and increase the pH to prevent AMD. The tailings slurries are also often pre-treated with H_2O_2 and O_2

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in order to promote the oxidation of arsenite complexes into less mobile arsenate species. Gaining knowledge about the distribution and speciation of As in such tailings is essential for their future management. For this reason, we studied cyanided tailings from a mine in the north of Sweden where gold has been extracted from inclusions in arsenopyrite. The original ore and tailings (which had been pre-treated with $\text{Fe}_2(\text{SO}_4)_3$) were studied in detail by static and kinetic leaching experiments, analysis of their chemical composition and geochemical modelling. The specific objectives of this investigation were as follows:

- Chemically characterize the ore and tailings at the mine and speciation of As phases in each case.
- Determine the mobility of As under oxidizing conditions by static and kinetic leaching tests.

It was anticipated that these investigations would yield new insights into the geochemical processes governing As mobility at the studied mine and, in general, allow the development of more effective ways of managing As-bearing tailings that prevent the occurrence of high As concentrations in mine drainage.

2. Site description

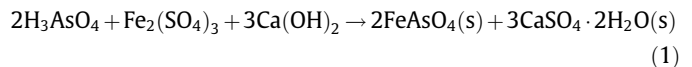
The Svartliden gold ore deposit is situated along the so called Gold Line (Fig. 1), southwest of the Skellefte ore district in northern Sweden. The operational time was 2005–2014 and until 2012, approx. 2.4 Mt of ore at a grade of 4.4 ppm Au was generated (Schlöglova et al., 2013). The Svartliden gold deposit is considered to be a structurally controlled epigenetic lode gold deposit (Hart et al., 1999; Bark and Weihed, 2003, 2012) with key features resembling orogenic gold style mineralization. Gold is the only economic metal at Svartliden. The mineralization is spatially associated with a banded iron-formation (Schlöglova et al., 2013; Sciuba, 2013) situated at the contact zone between metasedimentary rocks and amphibolites. The metasedimentary host rocks exhibit interbedded carbonaceous shale horizons with up to 30% pyrrhotite (Hart et al., 1999).

The mineralogy of the ore zone (including the banded iron-formation) constitutes mainly quartz, magnetite, diopside, hedenbergite, tremolite, grunerite, fayalite, pyrrhotite, arsenopyrite and löllingite (Sciuba, 2013). Gold occurs as electrum (Au/Ag alloy). The gold grain size ranges between 5 and +100 μm with an average grain size of ca. 45 μm , and the gold occurs as inclusions in arsenopyrite-hosted löllingite, commonly at the grain boundary to arsenopyrite and within arsenopyrite. Gold grains are also found in the silicate matrix, commonly spatially related to arsenopyrite (Bark et al., 2013).

3. Materials and methods

Tailings and crushed ore originating from the Svartliden Gold mine, Sweden were provided by the mining company Dragon Mining AB. Tailings have been deposited in a tailings impoundment at the mine for 8 years (2005–2013) at a rate of approx 0.3 million tonnes/year. Tailings were sampled at depths of 0–30 cm from approx. ten different locations on the impoundment and mixed to form a bulk sample of approx. 15 kg. The masses of the crushed ore samples were approx. 3 kg. The tailings slurries at the mine are routinely treated by aeration and hydrogen peroxide (H_2O_2) together with $\text{Fe}_2(\text{SO}_4)_3$ and lime in order to generate As-bearing Fe-precipitates (reaction (1)). Raising the pH in the solution helps to avoid the formation of AMD and toxic cyanide gas. Hydrogen peroxide is used to increase the oxidation rate of arsenites into

arsenates, which is the preferred species when considering the stability of As.



The pH of the treated effluent is reduced to 8–8.5 before deposition in the tailings dams, in accordance with legal guidelines.

3.1. Tailings and ore characteristics

The acid potential (AP), neutralization potential (NP) and net neutralization potential (NNP) of the tailings samples were determined in triplicate by the acid-base accounting (ABA) test according to Swedish standard (SS-EN 15875:2011). Tailings were dried at room temperature and sieved to a particle size of <0.125 mm before testing. Two grams of dried, sieved tailings were mixed in distilled water for 22 h with a magnetic stirrer, after which the pH of the suspension was determined. The suspension was then treated with 1 M HCl until its pH reached 2–2.5 and the mixtures were back-titrated to a pH of 8.3. Total sulphur content was determined by ICP-AES analysis.

Powder X-ray traces were conducted on a Siemens D5000 diffractometer using a Cu K_α radiation source (40 kV and 40 mA) over the range $2\theta = 5\text{--}90^\circ$ using a step size of 0.02° and scan rate of 1° per minute. Crystalline minerals present at proportions of <2 wt% were qualitatively determined.

From the primary ore and tailings, fifteen samples were prepared as polished sections and examined by optical and scanning electron microscopy for phase identification and textural analysis at the Luleå University of Technology. The electron microscope used was a Zeiss Merlin FEG-SEM equipped with energy- and wavelength-dispersive spectrometers. An accelerating voltage of 20 kV and beam current of 200–1000 pA were used for the analysis.

3.2. Leaching tests

Environmental assessment leaching tests (batch and weathering cell) were conducted to evaluate the behaviour of As in the tailings. Batch leaching tests (BLT) were performed to assess the leaching of selected elements from the tailings over the short term. Weathering cell tests (WCT) were conducted in duplicate to simulate weathering of the tailings over extended periods of time and to determine the kinetic release of specific elements.

Batch leaching tests (BLT) were conducted on tailings in triplicate according to the SS-EN 12457-4 standard (SIS, 2003). Tailings (100 g, dry weight) were placed in acid-washed bottles (1500 ml) together with 1000 ml of milliQ H_2O to generate a liquid/solid ratio of 10 (L/S = 10). The samples were agitated for 24 h in a rotary shaker (10 rpm). The leachates were then filtered through a 0.45-mm Filtropur S non-pyrogenic Sterile-R syringe filter (cellulose acetate membrane) into acid-washed bottles and stored cold (4°C) in darkness until analysis. The pH, redox potential (Eh) and electrical conductivity (EC) of the tailings were determined using unfiltered samples. The chemical compositions of the water samples were analyzed as described in the “Sample analysis” section.

In the weathering cell test (WCT), a modified version developed by Cruz et al. (2001) was used to simulate accelerated weathering of the tailings and assess the reactivity of their mineral content over time. This protocol was selected because it enhances evaporation and reduces the degree of saturation of the tested sample, avoiding reactivity inhibition. Approximately 70 g of tailings was placed on a paper filter in a Büchner-type funnel. The samples were exposed to weekly cycles, involving

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