Applied Geochemistry 93 (2018) 145–157

Contents lists available at ScienceDirect

Applied Geochemistry

journal homepage: www.elsevier.com/locate/apgeochem

Characterization of a gold extraction plant environment in assessing the hazardous nature of accumulated wastes (Kemerovo region, Russia)

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ARTICLE INFO

Handling Editor: Michael Kersten.

Keywords:
Arsenic
Komsomolsk tailings
Environmental pollution assessment
Electrical resistivity tomography
Economic evaluation

ABSTRACT

Geochemical and geophysical investigations were performed in the area of the Komsomolsk tailings impoundment. Gold ore tailings produced with cyanidation have been generated by the Komsomolsk Gold Extraction Plant. The relatively low sulfide content in the Komsomolsk tailings and the presence of carbonates result in a low acid production potential (AP) for these tailings. The tailings pond is characterized by neutral to slightly alkaline conditions and metal concentrations, except for those of As and Sb, below the maximum permissible concentration (MPC). The situation is complicated by the fact that the displaced Berikul tailings are stored in the southern part of the Komsomolsk tailings impoundment. Sulfide concentrate cyanidation tailings were produced by the former Berikul Gold Extraction Plant. In the Berikul tailings, the sulfide content is approximately 25%. This high content has resulted in a high AP and the formation of acidic and ultra-acidic surface ponds (pH ~2) with extremely high concentrations of metals and metalloids (As up to 4.1 $g L^{-1}$). The estimated duration of acid drainage generated by the Berikul tailings is approximately 2400 years. Surface drainage from the tailings enters the Voskresenka River; as a result, the concentrations of As and Sb in the river water approach the MPCs established by the Russian Ministry of Health. Based on electrical resistivity tomography (ERT), the uncontrolled leakage of acidic and highly mineralized solutions through a natural geological fault into groundwater horizons was revealed. Groundwater contamination was confirmed via an analysis of drinking water from a well located near the fault.

1. Introduction

The migration of chemical elements, especially As, Sb, Cu, Zn, Cd, and Pb, from mine tailings and waste has been widely investigated. High contents exceeding the maximum permissible concentrations (MPCs) of metals and metalloids in drainage and surface mine waters have been observed in many abandoned and active mining areas worldwide (Edraki et al., 2005; Meck et al., 2006; Cravotta, 2008; Cidu et al., 2013). Since the 20th century, there has been a significant focus on the geochemistry of acid mine drainage (AMD) and its impact on the environment. Many investigations have described the geochemical and mineralogical compositions of mine tailings and surface mine waters, as well as AMD geochemistry (Paktunc et al., 2003, 2004; Wang and Mulligan, 2006; Lottermoser, 2010; Blowes et al., 2014; Martin-Crespo et al., 2015; Korneeva et al., 2017). Over the past decade, considerable research has focused on understanding mine drainage generation and minimizing the associated effects on the environments.

There is a clear need to develop a more comprehensive approach for evaluating the environmental hazards associated with the release of metals and metalloids to the environment (Bortnikova et al., 2006; Gas'kova et al., 2008; Tolaymat et al., 2015). This approach should cover a wide range of processes that determine the fate of toxic elements in mining regions (Bortnikova et al., 2003). Monitoring of man-made lakes (tailings impoundment) or waste heaps using a combination of geochemical and geophysical methods can serve as a basis for developing a quantitative model of toxic element behavior in various

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https://doi.org/10.1016/j.apgeochem.2018.04.009
Received 29 November 2017; Received in revised form 12 April 2018; Accepted 21 April 2018

environmental compartments (lakes, pore water, silt solutions, bottom sediments buried tailings, etc.).

In the past fifty years, the numbers of studies of remediation in areas affected by mining activities and assessments of the influence of waste on the environment have significantly increased. Currently, most investigations of mine tailing areas are conducted using geophysical methods to determine the mine drainage distribution in a given coordinate space (Martín-Crespo et al., 2010; Placencia-Gómez et al., 2010; Martínez-Pagán et al., 2011; Martínez et al., 2012, 2016; Zarroca et al., 2015; Tycholiz et al., 2016; Olenchenko et al., 2016; Yurkevich et al., 2015, 2017a; 2017b) and trace the paths of toxic elements in mine waste (Kazakis et al., 2017).

Special attention has been given to the behavior, transport and deposition of arsenic as a particularly toxic element. Studies of arsenic toxicology and the associated hazards are closely associated with the development of available technologies for arsenic removal (Mondal et al., 2006; Choong et al., 2007; Fan et al., 2016; Cheng et al., 2017).

Various aspects of arsenic transport from stored tailings into the environment have been studied for many years and include the oxidation of sulfide- and As-bearing tailings (Bowell and Bruce, 1995; Blowes et al., 1998; Courtin-Nomade et al., 2003; Bodénan et al., 2004), arsenic modes of occurrence in tailings and the soil (Cullen and Reimer, 1989; Foster et al., 1998; Roussel et al., 2000; Savage et al., 2000; Bortnikova et al., 2010, 2012), and secondary As minerals in contaminated soil and waste systems (Drahota and Filippi, 2009).

New experimental simulations have been performed on the release of metals (Cu, Pb, Zn) and metalloids (As, Sb) from mine tailings (Paktunc et al., 2003; Walker et al., 2006; Abrosimova et al., 2015a) and their subsequent adsorption on formed iron hydroxides (Fuller et al., 1993; El Adnani et al., 2016; Hiller et al., 2016) in addition to studies of As behavior in soil (Dousova et al., 2012) and in As-rich tailing profiles (Armienta et al., 2012), metalloids intake by plants from contaminated soils (Cidu et al., 2014; Simmler et al., 2016) and accumulation in organic-bearing material can be used for remediation of polluted areas as well as for secondary enrichment technologies (Sarygool et al., 2017).

The arsenic limit in drinking water and reservoirs for domestic use recommended by the World Health Organization (WHO) and Russian Ministry of Health is 10 $\mu g\,L^{-1}$ (WHO, 2011; RMH, 2003). However, an As concentration of approximately 10 $\mu g\,L^{-1}$ may still cause cancer (Quansah et al., 2015).

Current information regarding the area near the Komsomolsk tailings impoundment after the undigested placement of the Berikul tailings is not publicly available. Therefore, a relevant assessment with conclusions and practical recommendations should be submitted to the administration of the Kemerovo region. A science-based approach for environmental monitoring could provide a simultaneous assessment of the economic feasibility of the extraction of valuable tailings components.

The objectives of this article are as follows: 1) present new surface and groundwater composition data from two contrasting tailings sites; 2) perform an electrical resistivity tomography (ERT) survey to evaluate the volume of tailings in the impoundment; 3) determine the spreading direction of contaminated waters in the area of the Komsomolsk tailings impoundment; 4) provide a science-based approach for monitoring and protecting groundwater resources that can be applied in other mine-impacted areas; and 5) estimate the environmental damage to polluted waters and assess the economic feasibility of extracting valuable components from the tailings.

2. Study area

The Komsomolsk gold deposit is located in the Eastern Kemerovo region, Russia. It is a system of gold-arsenopyrite-quartz veins with a large stock of gabbroids. The deposit was mined from 1937 to 1999. The primary sulfide minerals are pyrite, pyrrhotite, and arsenopyrite with lower contents of galena, sphalerite, and chalcopyrite (2–2.5% of the total deposit). Quartz, feldspar, and mica are the most abundant gangue minerals, and some carbonate grains (calcite and dolomite) are present (~6%). The ores of the Komsomolsk deposit were processed using cyanidation techniques with NaCN at the Komsomolsk Gold Extraction Plant (KGEP). Gold precipitation was performed with zinc dust, and the main product was Au sludge. In addition, KGEP produced gold extracted from the antimony sludge (the remaining product after leaching antimonite concentrates using Na_2S and NaOH) of the Kadamjai Plant. This sludge constituted a small portion of the mine waste (0.5 tons of sludge was added to every 100 tons of ore) but was rich in metal contents.

The KGEP tailings are located in the territory of the Komsomolsk settlement and 1 km to the northeast of the plant (Fig. 1S in Supplementary Material). The tailings have been present since 1964. The tailings impoundment is a natural ravine filled with slurry runoff. The tailings area is 146,000 m^2, and the amount of solid accumulated material is ≈ 1.1 million m^3, or 3.5 million tons. The impoundment is topographically enclosed on three sides and by a bulk dam on the fourth side. A tailings pond formed at the surface due to particle accumulation and consolidation. The pond area is ≈ 60,000 m^2, and the average depth is 2 m. Currently, the pond is primarily replenished by seasonal atmospheric precipitation. At times, the pond water flows under the dam to the surface and then enters the Voskresenka River. Descriptions of the mine tailings and mineralogical data were provided in previous works (Lazareva et al., 1999; Gas'kova et al., 2000; Shuvaeva et al., 2000). We should emphasize that the tailings impoundment is located near a living area in the Komsomolsk settlement. Recently, the population has perceived the water body as a “natural” pond, and it is actively used for domestic purposes (Fig. 2S (a) in Supplementary Material).

Additionally, after the cyanide leaching of sulfide flotation concentrate from the Berikul Gold Extracting Plant (BGEP), 100,000 tons of tailings was transported and stored in the southern portion of the tailings impoundment in 2004 (Fig. 1S in Supplementary Material). The Berikul gold mine was situated 20 km from Komsomolsk and exploited the gold-sulfide-quartz veins of the Staro-Berikul and Novo-Berikul deposits. The main ore minerals were quartz, calcite, pyrite, pyrrhotite, arsenopyrite, and chalcopyrite. Sphalerite, galena, tennantite, tetrahedrite, dolomite, ankerite, gold, silver, burnonite, and bornite were minor minerals (Alabin and Kalinin, 1999). The mine was worked between 1942 and 1991, and ores were processed at the BGEP. According to BGEP archives, flotation concentrate was produced during primary processing. Additionally, gold was extracted from sulfides using cyanide-based techniques. After the removal of the Au-bearing cyanide solutions, the sulfide flotation residues were neutralized by adding $Ca(ClO)_2$ before being dumped onto waste piles. Previously, this waste was stored in bulk at the Old Berikul settlement (Gieré et al., 2003; Sidenko et al., 2005). Initially, there was a plan to extract gold from these tailings at the Komsomolsk Plant, but the lack of cost-effective technology and the high toxicity of the waste did not allow for the implementation of this plan. As a result, the Berikul tailings are stored in the southern part of the Komsomolsk tailings impoundment. The amount of solid accumulated material totals 100,000 tons. The discarded material contains more than 25% of fine-grained sulfides, including pyrite (35–40 wt%), arsenopyrite (2–5 wt.%), and minor amounts of pyrrhotite, sphalerite, chalcopyrite, and galena. Among the gangue minerals found in the waste, the predominant phases are quartz (30–35 wt%), albite (5–10 wt%), chlorite (5–10 wt%), and calcite (3–5 wt.%) (Gieré et al., 2003). Many secondary minerals have been described in the waste (Gieré et al., 2003; Sidenko et al., 2005). The ponds were formed by seasonal precipitation immediately on top of the displaced Berikul tailings (Fig. 2S (b) in Supplementary Material). The volume and configuration of the ponds seasonally changes. The pond water has a brownish-black to light red color. Interactions with highly oxidized tailings led to the formation of the current hydrochemical