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TECHNICAL ARTICLE

Geoenvironmental Study of Gold Mining Tailings in a Circular Economy Context: Santa Barbara, Minas Gerais, Brazil

M. G. Lemos[1,2] · **T. Valente**[1] · **A. P. Marinho-Reis**[1,3] · **R. Fonsceca**[4] · **J. M. Dumont**[2] · **G. M. M. Ferreira**[2] · **I. D. Delbem**[5]

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Abstract

We characterized the tailings from the Santa Barbara tailings dam, which is located in Minas Gerais, southeastern Brazil, to: (i) identify its chemical, mineralogical, and metallurgical properties, and (ii) perform an environmental evaluation of the water at the surface of the tailings facility. The potential recovery of elements such as Sb, As, and Au was also considered for potential tailings reuse. The water was alkaline, with maximum pH values of ≈ 10, and contained potentially toxic elements, such as Sb (up to 0.500 mg/L), As (up to 0.080 mg/L), and Cu (up to 20 mg/L). Gold enrichment areas were found in the tailings dam, with concentrations up to 0.5 g/t. Alignment exists among tailings management, demand for critical raw materials, and increased interest in the processing of low-grade ores and mining waste, which is important in the context of the circular economy. They suggest that valorisation of tailings, although challenging, can be achieved by economic recovery of the more valuable metals.

Keywords Geochemistry and environmental mineralogy · Tailings dam · Environmental risk assessment and characterization

Introduction

The amount of waste rock and tailings produced over a mine's life cycle depends, among other aspects, on the extraction process, the concentrations of valuable minerals, and the location of the deposit. The exact quantification of the produced waste is complex due to the diversity of operations and technologies used in extraction and beneficiation processes (Souza Junior et al. 2018). While variable, the volume of mine wastes is almost always high. Lottermoser (2007) estimates the ratio of tailings to concentrate is generally around 200:1. The total non-coal mine waste lying in dumps around the world was estimated in 1985 at 50,000 Mt; of this, 33% were tailings, 17% dump/heap leach wastes and mine water, and 50% surface and underground waste rock (1985 Report to Congress, after Wilmoth 2000 in Twardowaska et al. 2004). According to Blight (2011), South Africa's gold mining industry produced 7.4×10^5 t of tailings from 1997 to 2006. In Brazil, it is estimated that 3.8 M oz. of gold can be found in old tailings dam(s) operated from 1834 to 1982.

In the traditional metal mining sector, waste rock dumps and tailings dams are among the infrastructures with the greatest environmental impact. Tailings are especially contaminated due to their fine particle size and comparatively high surface area, which sorb contaminants (Hudson-Edwards et al. 2008) and can chemically change after deposition (Kossoff et al. 2014). The generation of tailings can have serious negative repercussions for stakeholders and the global economy (Gaustad et al. 2017). Therefore, industrial water supply and contamination by potentially toxic elements are worldwide environmental problems in the mineral sector (Acheampong et al. 2010).

✉ M. G. Lemos
mglemos@anglogoldashanti.com

[1] Institute of Earth Sciences, Pole of University of Minho, Campus of Gualtar, 4710-057 Braga, Portugal

[2] Anglogold Ashanti, Mining and Technical, COO International, Nova Lima 34000-000, Brazil

[3] Geobiotec, Departmento de Geociências, Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

[4] Institute of Earth Sciences, Pole of University of Évora, University of Évora, 7000 Évora, Portugal

[5] Microscopy Center, Universidade Federal de Minas Gerais, Belo Horizonte 31270-013, Brazil

In Brazil, in addition to this reality and a linear economic model approach, the latest Mariana and Brumadinho-Minas Gerais tailings dam failures (respectively, Nov. 2015 and Jan. 2019), drew attention to the sector's problems and enhanced the difficulty of obtaining environmental permits and suitable places for tailings disposal. Consequently, the mining industry faces increasing economic, social, and environmental challenges. The need to ensure sustainable mining in compliance with legal environmental frameworks is leading the sector towards a new paradigm.

The key component of the circular economy is extending the useful life of raw materials that have already been extracted from the ecosphere (Gaustad et al. 2017) in a restorative perspective that minimizes systemic risks by managing finite inventories and renewable flows of resources (Araújo et al. 2017; Ellen Macarthur Foundation 2013). Besides this, according to the latest British supply risk list of chemical elements (British Geological Survey 2015), rare earth elements (REE), antimony (Sb), germanium (Ge), bismuth (Bi), as well as arsenic (As), platinum group elements (PGE), and cobalt (Co) are potentially subject to high levels of risk of supply disruption. In this context, Tayebi-Khorami et al. (2019) suggest five main areas of integration within the mining sector: social dimensions, geoenvironmental aspects, geometallurgy specifications, economic drivers, and legal implications. Considerable research and development are still necessary to identify effective solutions in each of these key areas. There are several broad ways to do this in the mining context, including residue valorisation, wherein the residues formed during the metal extraction process are valorized (i.e. transformed into a product with value). It also involves processing residues, such as wastewaters, waste solvents, solid residue, exhaust gasses, and ashes (Singh et al. 2020; Spooren et al. 2020). Reuse and reprocessing of tailings are possible approaches but require characterization efforts supported by robust geochemical and mineralogical techniques. These include x-ray diffraction (XRD) and x-ray fluorescence (XRF) in association with quantitative electronic mineralogy (Pires et al. 2019) for mineralogical characterization, automatic quantification of mineral phases, time-of-flight secondary ion mass spectrometry (TOF–SIMS), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), and electron backscatter diffraction (EBSD) (e.g. Guanira et al. 2020; Martin et al. 1997; Novhe et al. 2018; Parbhakar-Fox 2016; Shi et al. 2009; Silva et al. 2004).

Biosorbents and nanofibers may prove to be a way to recover metals such as Cu, Pb, and Cd from effluent water (Sang et al. 2008; Li et al. 2013), and precious metals can potentially be recovered from mine waters and leachates as well. Other approaches, such as ion flotation, suggest good recovery for Cu (Jafari et al. 2017). Acid mine drainage (AMD) remediation has high costs, but could represent a source of metals, as shown by Skoronski et al. (2017), through recovery of Al and Fe contaminants in usable forms, and show new forms to minimize the cost of water treatment (Akinwekomi et al. 2020, Ryan et al. 2017). The work of Antunes et al (2010); Hedin (2003); Silva et al. (2019); and Valente et al (2016) indicate the potential of recovering ochre-precipitates from passive AMD treatment, for use as pigments and in the ceramic sector. Also, Grande et al. (2013) presented a system to neutralize AMD and recover its metal load, using energy obtained from renewable sources. Thus, neutralization and treatment could serve the purpose of reducing environmental liabilities while generating income, in agreement with the circular economy paradigm (Valente et al. 2016).

There are many examples of case studies and implementations for recovering metals and metalloids from mining waste. An example of current development is vitrification of contaminants such as As and Sb (US9981295B2—Dundee Sustainable Technologies 2016), which has been implemented at gold mines in South Africa, Canada, and Brazil. Sensor-based technologies can be useful in coarse wastes and old stockpiles to reprocess and recover tin, tungsten, and gold (Manoucheri et al. 2016; Robben et al. 2020; Von Ketelhodt 2009). Altinkaya et al. (2019) suggested new approaches to recover trace metals from sulfide flotation tailings in cupric chloride solutions; recoveries of Cu, Ni, Zn, Co, Fe, and Au exceeded 58%. Pretreatment of cyanide tailings by magnetic roasting and its effect on the followed comprehensive recovery of valuable metals were investigated in Liu et al. (2013). The results indicate that the leaching rate of gold reaches 46.1% and that the magnetic susceptibility of iron is up to 86.3%. In addition, there are opportunities for extracting precious metals and other critical substances like Ag, Pt, In, Ge W, Cu, Zn, Pb, and Sb via common metallurgical routes, using regrinding, flotation, roasting, leaching, bioleaching, etc. (e.g. Chen et al. 2014; Dehghani 2009; Falagán 2017; Martin et al. 2015).

The present study applies the concept and goals of the circular economy to gold processing tailings in Santa Barbara, MG, Brazil. The main aims are to: (i) evaluate the quality of the surface effluent water; (ii) present an integrated physical, geochemical and mineralogical characterization of the solid tailings; and (iii) understand the chemical and grade distribution and potential for metallurgical extraction of various elements from the tailings dam. Overall, the study demonstrates the potential of recovering metals in a conceptually linear process, promoting a more sustainable Study Site.

The study area is in the Iron Quadrangle (QF), a metallogenetic province that hosts large gold and iron deposits, in addition to industrial gems and minerals (Porto 2008). The QF represents one of the most important geotectonic unit with rocks and geological evolution of Archaean and Proterozoic ages (Almeida 1967). Three main tectono-stratigraphic domains compose the QF province: granite-gneissic terrains, a sequence of greenstone belt type (Rio das Velhas Supergroup—SGRV), and a supracrustal sequence of chemical and clastic sedimentary rocks (Minas Supergroup). The Rio das Velhas Greenstone Belt, largely located in the State of Minas Gerais (Fig. 1a), is the most important gold district in Brazil, with an estimated 4.5% (936 t) of the world's ore reserves (Goldfarb et al. 2001; Lobato et al. 2001b). From the bottom to the top, it comprises tholeiitic mafic volcanic rocks and komatiites, banded iron formations of the Algoma type, metavolcanoclastic schists and phyllites, and terrestrial clastic sequences, all metamorphosed into greenschist to amphibolite facies (Fig. 1b; Almeida 1976; Schorscher 1978). The mineralized bodies, hosted in Archaean rocks, are structurally associated and controlled by hydrothermal alteration.

The Santa Barbara tailings dam is located in the northern part of the QF, in Santa Bárbara, Minas Gerais, 110 km from Belo Horizonte (Fig. 1). Underground mine waste from gold metallurgical plants has been deposited in this structure (Fig. 1c) since 1986.

Santa Barbara has a tropical climate with dry winters and humid summers. The hottest month is February, with an average temperature of 27 ºC, and the coldest is July, with 13.6 ºC. The average annual rainfall is 1897 mm, higher in the summer (IBGE 2019).

The Santa Barbara tailings dam lies within the geological context of the Córrego do Sitio unit (Baltazar 1998). The Córrego do Sítio unit is a metamorphosed turbidite in an alternating sequence of metagraywacke and phyllites, enclosing metamafic dikes and sills. The ore zone lies at the stratigraphic discontinuity between metasedimentary and metamafic rocks. The gold is associated with arsenopyrite and pyrite, which are disseminated in metapelitic rocks and quartz-carbonate veins. The mineralization includes several stages of crystallization: (1) pyrite and pyrrhotite, (2) arsenopyrite, pyrrhotite, and fine pyrite, (3) arsenopyrite with pyrrhotite and sulfosalts in quartz vein, and (4) pervasive pyrite (David 2006; Porto 2008). The sulfosalts are mainly represented by berthierite.

The mined ore feeds the metallurgical plant, where it undergoes: (1) crushing, (2) grinding, (3) gravimetric separation, (4) sulfide flotation, (5) pressure oxidation in an autoclave, and (6) leaching. Currently, only 25% of the run-of-mine (ROM) mass is used to recover gold, with variations related to the ore type treated (Lemos et al. 2019), resulting in different volumes and gold grades in

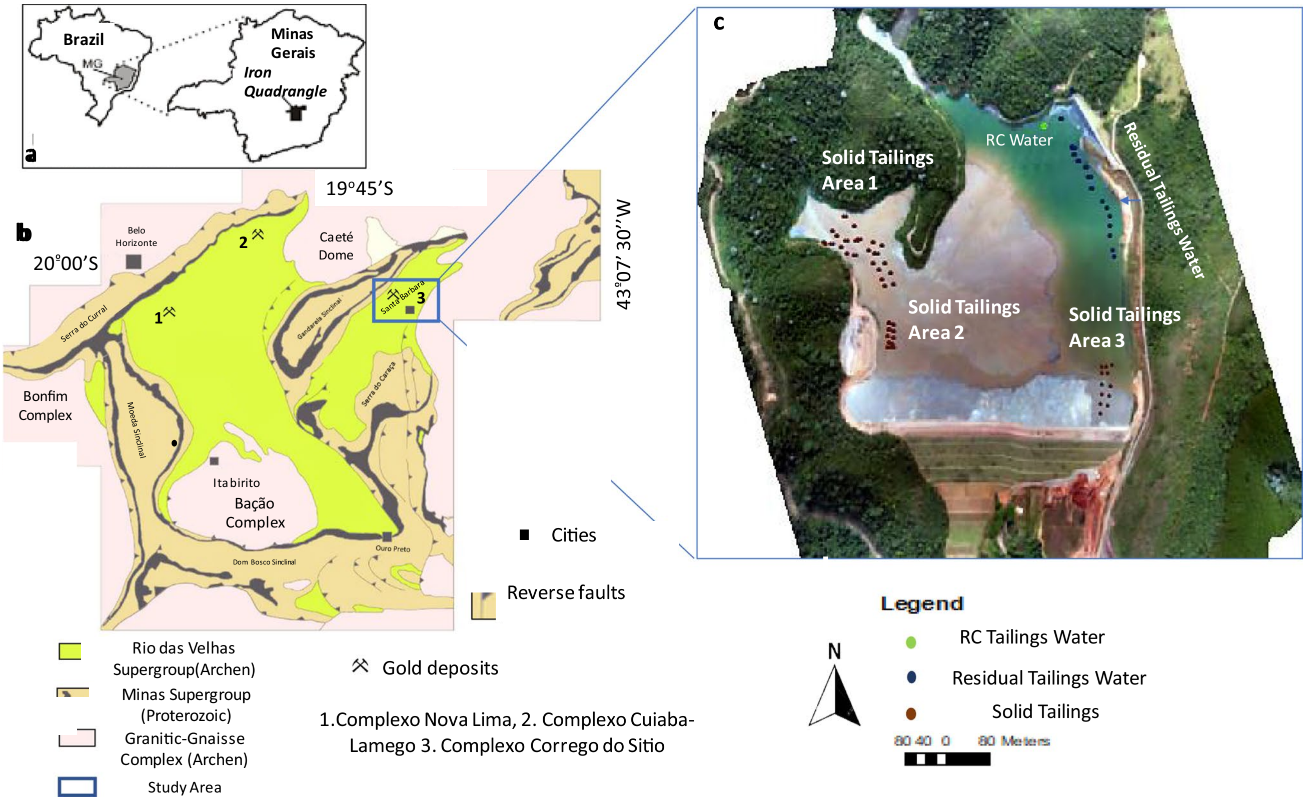


Fig. 1 **a** Location of study area; **b** Iron Quadrangle map (modified from Alkmin et al. 1998; Ruchkys et al. 2013; Porto 2008); and **c** sampled area (SIRGAS2000 – 14–06-2019)

the deposited tailings. Water from the metallurgical process is reused without treatment (RC—Fig. 2c).

The Santa Barbara tailings dam was built using a centerline method and spreads over a 25 km^2 area (Fig. 2). Water and solid tailings from the flotation and leaching operations are deposited in this structure with a capacity of 5MM m^3 of tailings (AGA 2018). After the Brumadinho tragedy, only last-stage tailings are collected in the dam, since all flotation tails now pass to a dry stack process. However, from 1986 to 2019, the dam received considerable volumes of mine tailings, thus suggesting considerable potential for reuse studies.

Materials and Methods

Sampling occurred during the end of winter and early spring (from late August to late September 2019). In this season, the weather varied between dry and humid periods, with rainfall occurring in the late afternoon. Temperatures ranged from 19 to 25 °C (IBGE 2019). The water samples were collected in the flooded areas (total 14 sites—Fig. 1b) and from the catchment that stores the water tailings reused in the metallurgical plant (total of 10 water samples representing one month period, three times per week). The water was stored in polyethylene bottles and kept at a 4 °C until analysis. Samples for metal analysis were acidified with HNO_3 to avoid precipitation.

A total of 123 sediment samples were collected using an auger, drilling up to 2 m (Fig. 1b). The dam was divided into three regions that were dry and had safe access. The distance between the samples ranged from 13 to 20 m, depending on the sampling area.

In the laboratory, parameters such as pH, Eh, turbidity, and electrical conductivity of effluent water samples were obtained using methodologies from the Standard Methods of Water and Wastewater (APHA 2005). Water samples were filtered using a 0.45 µm filter (Sigma Aldrich) and subjected to chemical analysis for Fe, Al, S, As, Cu, Sb, and Au by inductively coupled plasma mass spectrometry (ICP-MS) at Universidade Federal de Minas Gerais (UFMG) water analysis laboratory.

Chemical analysis of the solid tailings was performed by atomic absorption spectroscopy (AAS using AAS280 FS Varian) to determine Cu, As, Sb, S, and Fe. Fire assaying was used to obtain analytical gold data from the tailings. The choice of these elements was based on ore mineralogy and concentrations during production monitoring.

All the reagents used were of analytical grade. All metal solutions were prepared from concentrated stock solutions (Sigma Aldrich). High-purity water (HPW) was produced with a Millipore Milli-Q Academic system, which was used throughout the analytical process. Each sample batch prepared for ICP-MS and AAS analysis included water samples, duplicates, blanks, and standard reference materials for quality assurance and quality control (QC/QA) procedures. The Certified Reference Materials Si81 (Rocklabs) for solid tails were selected to represent a wide range of total elemental concentrations. Results of method blanks were always below detection limits. Values for precision (expressed as RSD %) were typically less than 15% for all elements.

In addition to the geochemical data, polished sections were prepared for mineralogical characterization. The mineralogical study was carried out using optical microscopy and scanning electron microscopy (SEM, Field Electron and Ion Company, FEI) at UFMG, Belo Horizonte. The samples were analyzed in a FEI electronic microscope, Quanta 600 FEG, high vacuum mode, coupled to the automated analyzer software (MLA—mode GXMAP and SPL-DZ) and the EDS Espirit Bruker (20Kve) microanalysis system.

To evaluate the potential of recovering metals and metalloids such as Au, Sb, and As, three batch tests were

Fig. 2 **a** Operational unit and tailings dam. **b** Panoramic image (bird's eye view) of residual water tailings

conducted on samples composed of solid wastes representing the three areas (Fig. 1c). The first test was an attempt to recover Sb and As thermally (Dundee Sustainable Technologies 2016; Liu et al. 2013; Padilha et al. 2014) by volatilizing and collecting it downstream as an oxide byproduct. The goal was to volatilize the Sb in the kiln in an inert or reducing atmosphere, separating it from the gangue material, and then oxidize it as it exited the kiln body. The experiment was conducted in a rotary horizontal quartz kiln, in a single stage with a final temperature of 850 °C, for 350 min in an atmosphere of 20% CO and 80% N_2. The second test was conducted in two stages with a final temperature of 930 °C, 994 min, and an atmosphere of 3% O_2 and 97% N_2. Another experiment was made in a wet, high intensity magnetic separator (WHIMS) as some successful applications of this methodology for iron, copper, and lead recovery from tailings have been described (Guest et al. 1988; Rao et al. 2016). The test occurred in five stages to reproduce a high grades Sb concentrate. A 200 g sample of the solid tailings was processed using an Eriez L4 WHIMS unit. Tailings from each separation were reprocessed at successively higher magnetic intensities (1500–10,100 G). For Au recovery, well-established bottle roll tests were performed in an agitated cyanide leaching solution at a pH of 11. Oxygen levels, alkalinity, acid consumption, and other parameters were monitored and strictly controlled.

Results and Discussion

Surface Effluent Water

Table 1 presents the physical and chemical parameters of the water collected from the tailings dam's surface. Liquids samples from accumulated flooded areas (RP) were compared with samples taken over time from the point of return to the plant (RC – Fig. 2b). Mine waters are very often acidic due to the water–rock interaction processes involving sulfides, but neutral to alkaline waters are also common and may present high concentrations of metals and metalloids (Nordstrom 2011).

In the present study, the results (Table 1) indicate that water quality was controlled not only by the ore deposit geology, but especially by the processing conditions in the hydrometallurgical plant. Therefore, sulfate occurs in high concentrations (1683–1914 mg/L in RP), in accordance with the ore mineralogy characterized by the presence of sulfides (pyrite, pyrrhotite, arsenopyrite). However, there are no AMD conditions as minimum pH is around 8, reaching a maximum of 10, reflecting the alkaline products used for extraction of gold with cyanide solutions. Therefore, as referred by Dold (2014), the general properties are typical of the operational phase of mining tailings, with an alkaline pH-Eh regime, and high concentrations of sulfate, metals (Cu), and metalloids mobilized from the primary minerals.

Climatic conditions control the evaporation/concentration and leaching/dilution cycle at tailings dams. Consequently, the difference between the residual and recirculated water may be due to these effects since the RC samples were collected over a two month period with rainfall; thus, the concentration changes could be due to dilution, in addition to these other parameters.

Comparing the two samples groups suggests a decrease in the mean values of some of the RC parameters, including sulfate, As (which decreased by ≈ 40%), and especially Cu, which changed from 23.6 mg/L in RP to 5.23 mg/L in the recirculated water (a decrease of ≈ 78%). The variability observed for Au in the RP was also noteworthy. Comparing the results, the Cu values were generally above the discharge limits in Brazil (CONAMA 2005). Therefore, this characteristic is another motivator for studying the effluent for reuse of metals.

Table 1 Statistical summary of effluent water physical–chemical parameters and dissolved EC electrical conductivity SD – Standard deviation

Physical Parameters	RC WasteWater (*N* = 10)				Resudial WasteWater (*N* = 14)			
	Mean	Max	Min	Stdesv	Mean	Max	Min	Stdesv
Turbidity (NTU)	17.0	65.0	4.56	13.7	22.00	40.00	9.00	8.36
eC (um/cm)	2822	4058	2414	353	3390	5076	2077	770
pH	8.60	9.71	8.00	0.449	8.56	9.90	7.80	0.512
eH	234	264	214	14.8	250	288	215	23.6
Metals (mg/L)								
Au	< 0.05	< 0.05	< 0.05	0	0.136	0.17	0.07	0.022
Fe	0.264	0.315	0.22	0.034	0.208	1.96	0.04	0.206
Al	0.310	0.386	0.247	0.051	0.278	0.35	0.12	0.042
Cu	5.23	11.4	3.37	1.77	23.6	24.9	21.0	0.769
Sb	0.645	0.652	0.632	0.009	0.639	0.664	0.610	0.023
SO_4	1683	1759	1570	75.6	1754	1914	1683	54.9
As	0.046	0.074	0.023	0.012	0.075	0.15	0.06	0.021

Solid Tailings

Among physical properties, grain size is a key issue to consider, both for environmental implications and potential for economic recovery. Many properties, such as specific surface area, are dependent on particle size. Consequently, processes such as adsorption/desorption, dissolution rates, and the general reactivity of the tailings are controlled by grain size fractionation. Figure 3 shows the average particle size distribution of the Santa Barbara dam samples. Results indicate that 80% pass through a 40 µm sieve. Thus, similar to many other tailings storage facilities (e.g. Nengovhela et al. 2006), this profile is dominated by silt and clay sized particles.

The chemical composition of the tailings is presented in Table 2 as a statistical summary for the sampled areas (Fig. 1c) and the two depths. In general, the Au mean grades were 0.505 g/t for the first sampled meter (S1m) and 0.684 g/t for the second sampled meter (S2m).

The mean concentrations of elements such as S, As Fe, Sb, and Cu are respectively 0.741%, 0.056%, 2.50%, 0.159%, and 0.012% for S1m and 0.860%, 0.042%, 2.62%, 0.194%, and 0.009% for S2m. The mean grades showed low variation by depth and a slight trend to increase in samples collected from the second meter (with some exceptions in Areas 2 and 3 – Fig. 4). Evaluating the grades by sampled region, Area 1 had the samples with the highest grades of Au, S, and Sb. The distributions by metals and metalloid by depth and area are illustrated in Fig. 4. The distribution can be associated to the variability of the metallurgic plant during the production process, spilling pulses, and migrating spilling points that caused local enrichment of individual phases like sulfides, as reported by others, e.g. Redwan et al. (2012). Besides this, after deposition, mine tailings could suffer geochemical and mineralogical evolution through weathering process. Therefore, these three assumptions together can explain the variations in content of samples collected from different areas and at different depths (Fig. 4).

Figure 5 also shows a correlation trend expressed as a Pearson correlation between the elements analyzed. For Au, a positive and not very significant coefficient of 0.42 was found for S; however, there is a negative trend for the mean grades of Au and As. Arsenic, Sb, Cu, and Fe presented higher positive correlation trends (e.g. 0.84 for Sb with As and 0.96 Sb with Fe). Table 3 shows an estimate of tonnage and respective element mean of content for the total area of the storage facility, considering the density of the tailings and two sampling depths.

Chemical and mineralogical characterization, using quantitative electronic approaches, are key tools for optimization of the extraction processes, in complex ores (e.g. Goodall et al. 2012) and in tailings storage facilities (Guanira et al. 2020). In the present study, the mineralogy of the tailings provides the knowledge needed to understand mineral associations, mineral liberation, and, consequently, to evaluate the potential for metal recovery.

Table 4 identifies the host minerals and how the elements of interest occur in the Santa Barbara dam. The

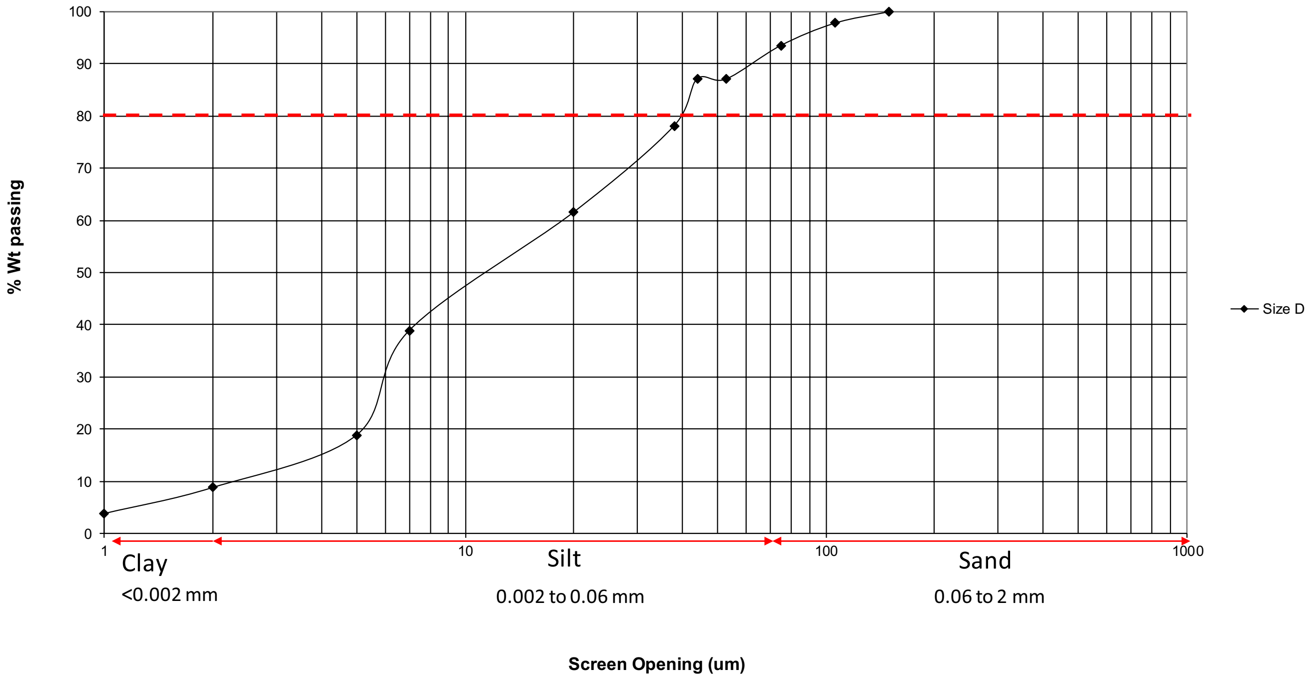


Fig. 3 Size distribution (Krumbein phi scale) of solid tailings from the Santa Barbara tailings dam

Table 2 Summary statistics of Au, S, As, Fe, Sb and Cu by Depth and Sampled Area

	Elemet	Deep (m)	Mean	StDev	Minimum	Maximum
Area 1 (N1m = 24 and N2m = 24)	Au g/t	1	0.619	0.119	0.470	0.910
		2	1.02	1.242	0.510	6.74
	S (%)	1	0.880	0.219	0.100	1.28
		2	0.925	0.127	0.750	1.21
	As (%)	1	0.065	0.072	0.001	0.170
		2	0.060	0.074	0.001	0.180
	Fe (%)	1	2.74	0.976	1.08	5.88
		2	2.87	0.897	1.74	4.90
	Sb (%)	1	0.189	0.258	0.002	0.808
		2	0.241	0.282	0.002	0.988
	Cu (%)	1	0.011	0.010	0.001	0.030
		2	0.009	0.009	0.001	0.040
Area 2 (N1m = 10 and N2m = 5)	Au g/t	1	0.316	0.098	0.250	0.590
		2	0.293	0.076	0.240	0.380
	S (%)	1	0.603	0.526	0.005	1.23
		2	0.957	0.074	0.900	1.04
	As (%)	1	0.156	0.029	0.100	0.190
		2	0.193	0.025	0.170	0.220
	Fe (%)	1	2.86	0.920	1.79	4.26
		2	3.20	1.73	1.71	5.09
	Sb (%)	1	0.197	0.053	0.090	0.270
		2	0.303	0.085	0.240	0.400
	Cu (%)	1	0.035	0.005	0.030	0.040
		2	0.040	0.000	0.040	0.040
Area 3 (N1m = 28 and N2m = 27)	Au g/t	1	0.474	0.173	0.290	1.20
		2	0.431	0.088	0.320	0.680
	S (%)	1	0.670	0.364	0.005	1.530
		2	0.805	0.256	0.005	1.130
	As (%)	1	0.013	0.011	0.001	0.050
		2	0.009	0.001	0.001	0.030
	Fe (%)	1	2.17	0.785	1.03	3.86
		2	2.34	0.975	1.03	4.25
	Sb (%)	1	0.120	0.236	0.002	0.830
		2	0.141	0.252	0.001	0.838
	Cu (%)	1	0.005	0.005	0.001	0.010
		2	0.005	0.005	0.001	0.010
Total (N1m = 62and N2m = 61)	Au g/t	1	0.505	0.176	0.250	1.20
		2	0.684	0.875	0.240	6.74
	S (%)	1	0.741	0.361	0.005	1.53
		2	0.867	0.208	0.005	1.21
	As (%)	1	0.056	0.068	0.005	0.190
		2	0.042	0.067	0.005	0.220
	Fe (%)	1	2.50	0.923	1.03	5.88
		2	2.62	1.01	1.03	5.09
	Sb (%)	1	0.159	0.226	0.002	0.830
		2	0.194	0.263	0.001	0.988
	Cu (%)	1	0.012	0.013	0.001	0.040
		2	0.009	0.011	0.001	0.040

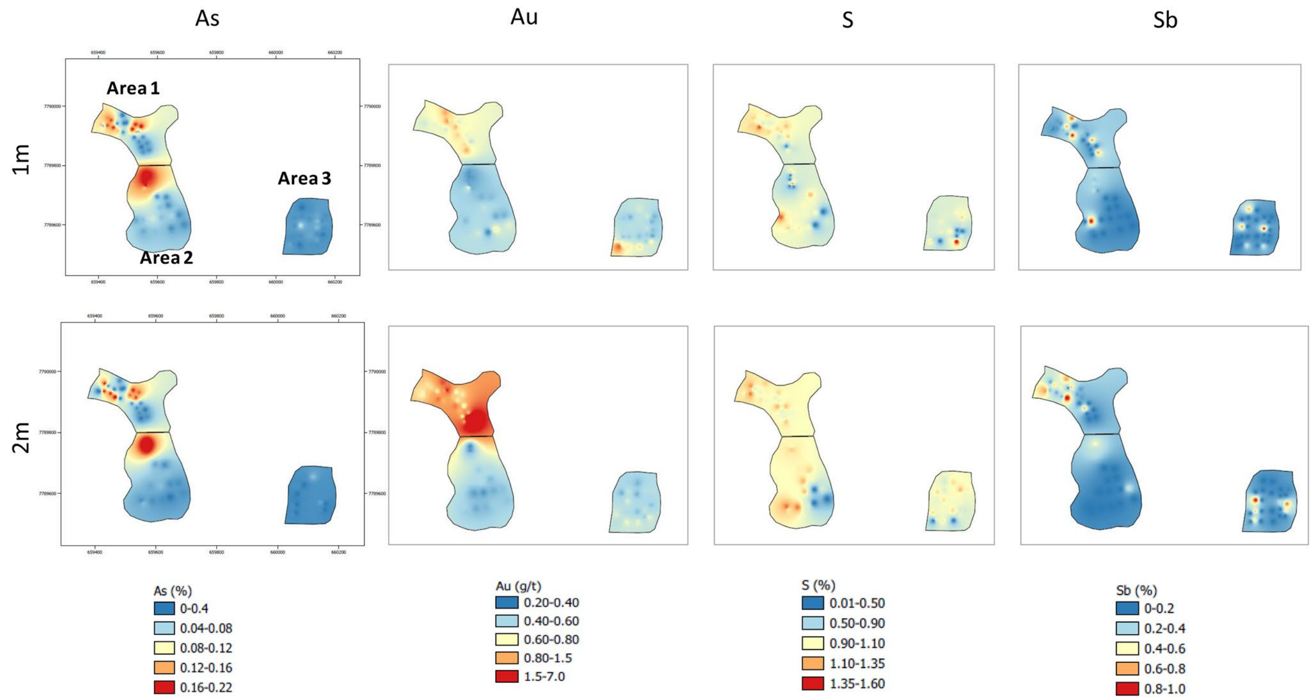
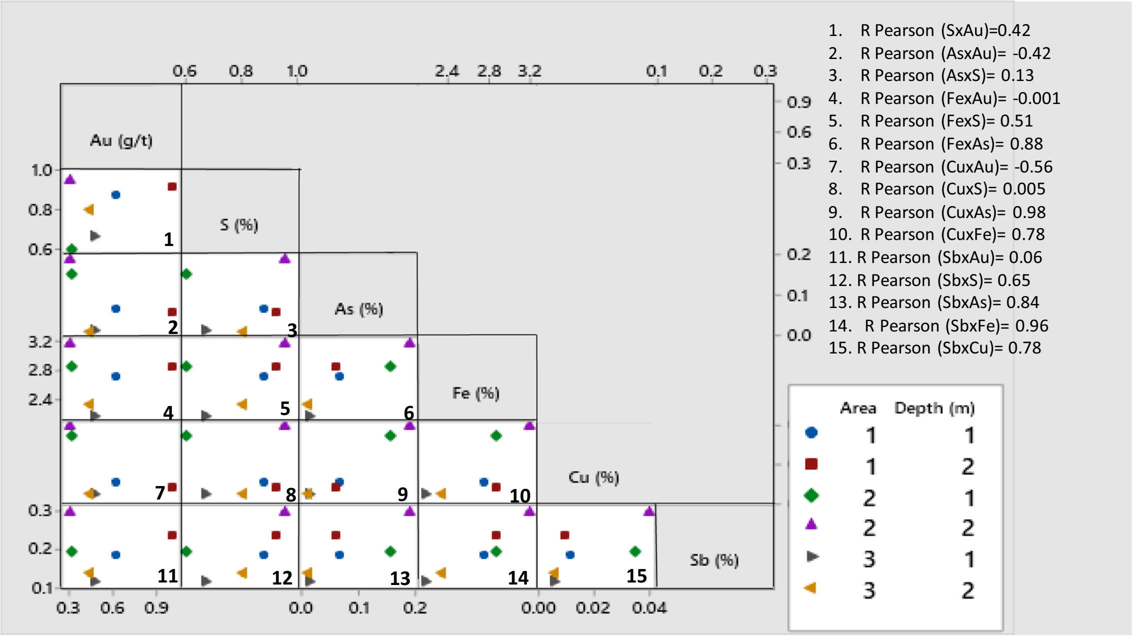


Fig. 4 Spatial distribution of As, Au, S and Sb by sampling depth and area



1. R Pearson (SxAu)=0.42
2. R Pearson (AsxAu)= -0.42
3. R Pearson (AsxS)= 0.13
4. R Pearson (FexAu)= -0.001
5. R Pearson (FexS)= 0.51
6. R Pearson (FexAs)= 0.88
7. R Pearson (CuxAu)= -0.56
8. R Pearson (CuxS)= 0.005
9. R Pearson (CuxAs)= 0.98
10. R Pearson (CuxFe)= 0.78
11. R Pearson (SbxAu)= 0.06
12. R Pearson (SbxS)= 0.65
13. R Pearson (SbxAs)= 0.84
14. R Pearson (SbxFe)= 0.96
15. R Pearson (SbxCu)= 0.78

Area	Depth (m)
● 1	1
■ 1	2
◆ 2	1
▲ 2	2
▶ 3	1
◀ 3	2

Fig. 5 Matrix plot of Pearson of Au, S, As, Fe, Cu and Sb mean values by area and depth

mineralogy comprises inherited minerals like quartz, muscovite, biotite, and phases formed during processing stages, such as gypsum, jarosite, and Fe-antimoniate. These latter two are sources of Sb, as can be seen in Fig. 6. Arsenic was also found to be associated with phases such as antimony oxide and rarely in arsenopyrite. Jarosite was the main host of Fe and S, instead of pyrite. Iron oxide/hydroxide was also identified in the samples. The source of Cu is chalcopyrite, but it was rarely detected.

Table 3 Estimated tonnage and element mean of contents for Au, As, Cu, Sb and S in Santa Barbara tailings dam

Element	Tonnes (kt)[a]	Grade	Element Content
Au (g/t)	853.5	0.504	13.83[b]
S (%)		0.804	686[c]
As (%)		0.049	41.82[c]
Sb (%)		0.177	151[c]

[a] Kt = t*1000 for 2 m sampled

[b] Koz

[c] t*1000

A special emphasis was given to the behavior of gold due to its economic value (Fig. 7). The following gold phases were detected: native gold, gold associated with Cu and Ag and aurostibite. Au particles were liberated and associated with jarosite and quartz, as illustrated by the false color image processed in multispectral linear arrays (MLA—right below in Fig. 7). The gold-containing phases are very thin, mostly less than 7 µm.

This mineralogical study provides additional information on and helps to understand the chemical behavior of the elements in the tailings dams. The correlations observed between the elements (Fig. 5) reflects their association with common mineralogical hosts. For example, Sb with Fe and

Table 4 Mineralogical composition of santa barbara solid tailings

Minerals	Chemical Formula	Wt%	Distribution and association
Quartz	SiO_2	35.6	Mainly liberated
Feldspar Group			Mainly liberated
Albite	$NaAlSi_3O_8$	1.11	
Anorthite	$CaAl_2Si_2O_8$	0.053	
K feldspar	$KAlSi_3O_8$	1.27	
Sheet Silicates			
Biotite	$KMg_{2.5}Fe_{2+0.5}AlSi_3O_{10}(OH)_{1.75}F_{0.25}$	1.26	
Muscovite Group	$KAl_3Si_3O_{10}(OH)_{1.9}F_{0.1}$	29.0	Mainly liberated and associated with quartz and Fe species
Chlorite	$(Mg,Fe)_3(Si,Al)_4O10(OH)_{2.}(Mg,Fe)_3(OH)_6$	5.01	
Oxides			
Iron Oxides/Hydroxides	Fe_2O_3/FeOOH	0.378	Mainly liberated and associated with jarosite
Rutile/Anathase	TiO_2	0.599	
Fe antimoniate	FeSb(As)O	0.806	
Carbonates			
Ankerite	$Ca(Fe,Mg,Mn)(CO_3)O_2$	9.00	Mainly liberated
Siderite	$FeCO_3$	7.20	
Calcite	$CaCO_3$	5.40	
Sulphates			
Gypisium	CaSO4 2H2O	1.00	Mainly liberated
Jarosite (With Sb)	$KFe(SO_4)_2(OH)_6$ & $(H3O)Fe(SO_4)_2(OH)_6$	2.00	
Arsenates			Enclosed in jarosite and silicates
Scorodite	$FeAsO_4\bullet_2(H_2O)$	0.049	
Sulphides			
Pyrite	$Fe^{2+}S_2$	0.080	Enclosed in jarosite and silicates
Pyrrhotite	$Fe^{2+0.95}S$	0.041	
Arsenopyrite	$Fe^{3+}AsS$	0.056	
Berthierite	$FeSb_2S_4$	0.141	
Chalcopyrite	$CuFe^{2+}S_2$	0.028	
Sphalerite		0.009	
Gold Minerals			
Native Gold	Au > 80%, Ag, Cu	(158)*	
Electrum	Au = 80%, Ag = 20%	(6)*	With quartz, gypsium, sulphides and jarosite
Aurostibite	AuSb	(146)*	

*()Number of gold mineral grains identified and characterized

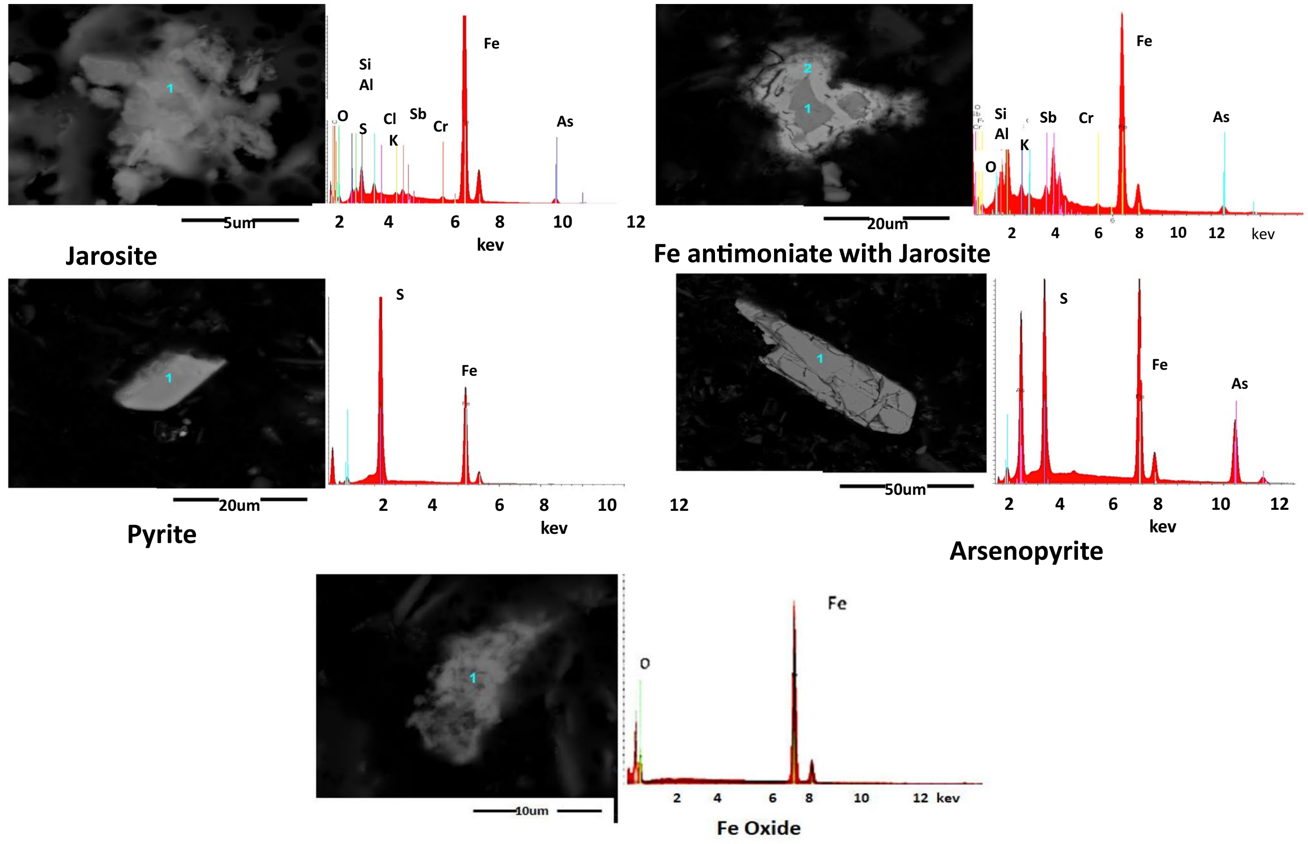


Fig. 6 SEM-SE images and respective EDS spectra of Fe species and sulfides

Sb with As, with a correlation of 0.84 and 0.96 occur in common phases.

Most of these elements are in phases transformed in the oxidation by pressure stages and associated with sulfides not recovered in flotation. Jarosite, iron antimoniate, and even iron oxide are suggested to be the result of the oxidation and precipitation of these elements from sulfides, such as berthierite and arsenopyrite (Berezowsky et al. 1984). Residual gold and sulfides represent extraction inefficiencies during the beneficiation, which results in co-precipitation/ encapsulation of elements like Sb and As in phases such as jarosite.

Batch Test to Recover Sb, As, and Au from Solid Tailings

According to the forms of occurrences of the metals and metalloid of potential value, such as Au, Sb, and As (Figs. 4 and 5, and Table 4), batch tests were conducted on solid tailings to check the feasibility of recovery. The highest reported Sb and As volatilization occurred in a two-stage roast as shown, together with the conditions tested, in Table 5. Even though Sb and As were associated with magnetic phases, the WHIMS test showed very low recoveries. The same behavior was observed for gold, with an extraction rate of 10%.

In a way, the results showed relatively low recovery rates, as expected due to the complexity demonstrated by the mineralogy and low content of these metals. However, the recoveries were obtained from composite samples and not in the most optimistic scenarios, that is, when performing selective extraction of the enriched areas (Fig. 4).

Therefore, the results indicate a need for review of the current experiments for increasing efficiency. Moreover, even though these metals are present as complex phases and the tailings are very fine (Fig. 6), such evaluations should be performed to precisely assess the potential of tailings for reuse.

Only a slight increase of grades by depth (Table 2) was detected, and the results were promising regarding the possibility of metal recovery, especially considering similar and new studies. Moreover, in accordance with the element supply risk list (British Geological Survey 2015), Sb and As were ranked in the highest risk category, enhancing interest in their recovery. Therefore, the data obtained in Santa Bárbara justify an effort towards more detailed studies, covering the entire area and depth of the

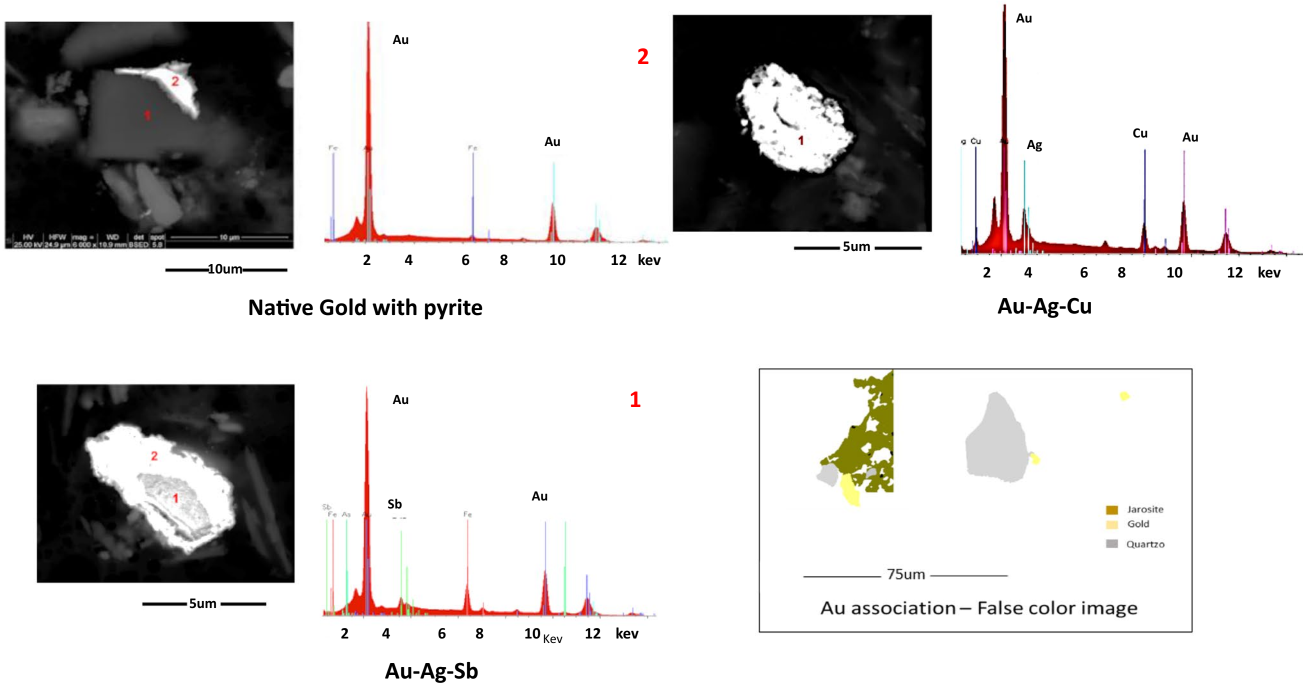


Fig. 7 SEM-SE images and respective EDS spectra of Au species and false image of Au associations (below right)

Table 5 Batch tests results of Sb, As and Au recovery

Experiment	Feed Grade	Overrall recovery (%)				
	Sb (%)	As (%)	Au (ppm)	Sb (%)	As (%)	Au (%)
WHIMS	0.2	0.05	–	3	6	–
1 stage klin roasting	0.2	0.05	–	4	6	–
2 stage klin roasting	0.2	0.05	–	19	7	–
Cyanide bottlerRoll	–	–	0.5	–	–	10

dam to accurately assess the recovery potential of these critical substances.

Conclusion

A gold process plant tailings dam was characterized for surface water and solids tailings up to 2 m deep. Information was obtained using integrated hydrochemical, geochemical, and mineralogical techniques. Moreover, it supported preliminary metallurgical testing and a more detailed view of the loss of Au, the main product of this operation. Mineralogical characterization demonstrated how metals and metalloids such as Sb, As, S, and Au occur in complex forms and detailed and innovative metallurgical tests must be performed. Therefore, and most importantly, the present study compiled a knowledge base that could support future decisions about the potential reuse of the tailings, while making clear how complex it would be.

The effluent water is alkaline, in accordance with the operation stage and the chemical products used in the treatment plant. The most important properties are the high concentrations of sulfate, Cu, As, and Sb, associated both with the mineralization and the process chemicals used for gold extraction. These results suggest the need for further research on metal recovery and improving the quality of the industrial water recirculated for the beneficiation process.

The characterization of the tailings solids confirms the need for reevaluation of the process routes already tested, in order to improve extraction efficiency. Also, the chemical and mineralogical compositions revealed the grades and occurrence modes of elements that are considered to be facing supply risk, such as Au, Sb, and As. Jarosite and Fe antimoniate are host phases.

Even considering that these metals occur in complex forms and the recovery of elements as Sb, As, and Au presented low rates in preliminary metallurgical tests, the results demonstrate the potential for reuse or refinement of the process for better use of the resource. Further efforts should be developed for an accurate calculation for the entire dam, which will allow more precise assessment of the recovery potential of enriched areas and to validate the aspirations in the context of a circular economy.

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