

Geoenvironmental Characterization of Gold Mine Tailings from Minas Gerais and Goiás, Brazil

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Abstract

For more than two centuries, sulfide gold ores have been treated at metallurgical plants located in Nova Lima, Santa Barbara and Crixás. Brazil. In this study, geochemical, mineralogical, and textural properties of tailings from eight tailings deposits were analysed. The samples show high concentration of Au, hosted in different minerals. In addition, samples contain S, Fe, and As. Sulfides, oxides, and sulfates are present, some as preserved relics. This work highlights different geochemistry and mineralogy, dependent on the nature of the tailings. Such information is critical to support long-term decisions about tailings management and circular economy.

Keywords: Environmental geochemistry, Mineralogy, Mining Railings, Brazil.

Introduction

Brazil is a country that has a strong relationship with mining, currently representing between 3 and 5% of GDP. This proximity has been noticed since the end of the 17th century, at the beginning of the first gold cycle. In the mid-18th century, Brazil produced approximately half of the world's gold, attracting the immigration of around 400,000 Portuguese, mainly in the region of Minas Gerais and Goiás (Fig 1).



Figure 1 Location of the main Au dams in Brazil (source: FEAM – State Foundation for the Environment) – Highlight for black dots for the study regions

Currently, this sector moves others through the supply of raw materials, such as the civil construction, automobile, aerospace, and other industries. Although its importance is relevant and strategic for the economy, the generation of waste is also important. The main deposition structures of these wastes are the dams and deposits (mine dumps). However, these structures may constitute mineral deposits with different chemical grades distribution and physical characteristics relatively to the exploited ore. With the evolution and dynamic changes in the market and technology, these wastes can thus provide an alternative to primary exploitation.

The tailings dams and other deposits resulting from the improvement of ores and/or Au metallurgical processes constitute waste accumulation infrastructures with two potential valences: focus of environmental impact due to the toxic substances they contain and possible sources of new raw materials.

The present work was carried out in active and non-active tailings dams, as well as depleted mine deposits around the cities of Santa Barbara (SB) and Nova Lima (NL) in Minas Gerais. In addition to these structures, the study also includes the active dam of a project in the city of Crixás (CR), located in the North of the district of Goiás.

The study, therefore, meets the concept and objectives of circular economy applied to tailings from gold processing. The main objective is to present an integrated physical, geochemical, and mineralogical characterization of solid tailings to support the detection of potential reuses and avoid possible environmental impacts.

Methods

The sampling stage took place during late winter and early spring (late August to late September 2021).

A total of 1560 sediment samples were collected with auger, drilling up to two meters for chemical analysis (at different depths). The distance between samples varied from 13 to 20 meters depending on the sampling area. In table 1 it is possible to verify the names of the studied structures, location, and types of samples.

In the laboratory, chemical analysis was performed by atomic absorption spectroscopy (AAS using AAS280 FS Varian) for the determination of Au, Cu, C, As, Sb, S, Fe. The fire assay was the procedure used to obtain analytical data for Au.

In addition to the geochemical data, polished sections were prepared

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

Results

Chemical Analysis

In the graph of fig 2, a box plot is presented with the variations and averages of the database surveyed, showing the chemical differences between the studied wastes. Sb is the main differentiator of solid samples from tailings deposits 6 and 7 in relation to other tailings. The Au concentrations are highlighted in structure number 5. The S is relevant for tailings 1, 4, 6, and 8.

In all deposits located in Nova Lima (deposits 1 to 5), higher As concentrations are observed in comparison with the others. The low levels in deposit 6 can be explained by the flotation stages, since all As sources are removed prior to their deposition in the dams (Lemos *et al.*, 2019). The others, 7 and 8, have low levels in the food sources of metallurgical plants (AGA, 2019).

Fe values are lower for tailings in area 3, being, on the other hand, high and variable for the others.

Cu concentrations are higher for deposits 7 and 8, despite deposit 4 having many outliers

Table 1 Information about the studied areas, collection methods, depth, number of samples and type of analysis. PSD – Particle size distribution; AAS - Atomic absorption spectroscopy; ICP (MS) – Inductively coupled plasma mass spectrometry

Area	Tailings Deposit	Sampling Method	Depth (–m)	Samples Numbers	Analysis
NL	1	Percussion+Diamond Probing	16	266	
NL	2	Percussion Probing	4.4	162	
NL	3	Direct push	4.0	615	AAS, ICP (MS),
NL	4	Direct push	6.7	286	Fire Assay, PSD,
NL	5	Direct push	12.5	257	Mineralogy
SB	6	Direct push	15	75	
SB	7	Percussion Probing	10	100	
CR	8	Percussion Probing	15	35	

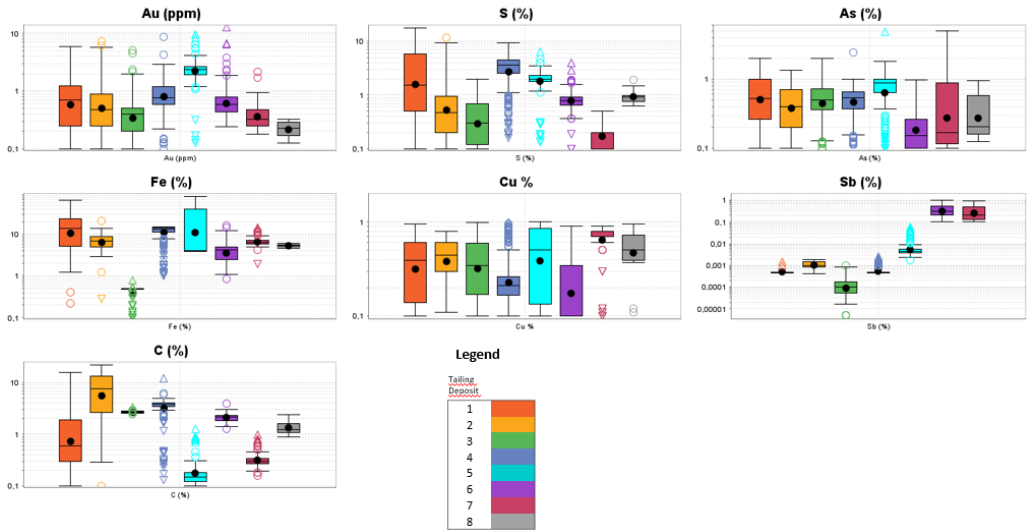


Figure 2 Box plot graphs demonstrating the variation and differentiation between the tailings of structures 1 to 8 studied for Au (mg/kg), S (%), As (%), Fe (%), Cu (%), Sb (%), and C (%) – Y (Logarithmic scale).

above the third quartile of the deposit. The C is variable for deposit 2, but on average higher than the other deposits.

Therefore, in the graph of Fig. 3 it is possible to differentiate the tailings in relation to the seven chemical variables. Three distinct

groups are noticed, being 1 represented by points close to the Au axis with most points of deposit 5. Group 2 are, in general, close to the Sb axis with most points of deposits 6 and 7. And a third group, with other deposits between the S, Fe, and C axes (Fig 3).

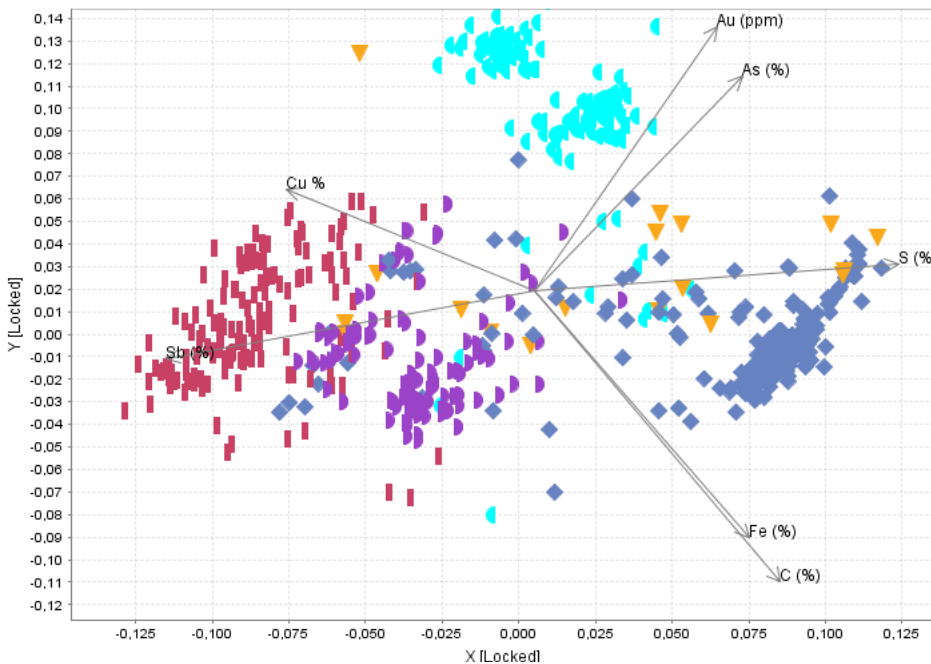


Figure 3 3D PCA graphics showing the grouping of chemical results from structures 1 to 8 studied for Au (mg/kg), S (%), As (%), Fe (%), Cu (%), Sb (%), and C (%) – Y (Logarithmic scale).

Mineralogy

Table 2 shows the mineralogy results of the structures under study.

In general, the gangue minerals are similar among the structures already studied (except for dam 5). However, with expressive differences between carbonates of the structure 1, composed of siderite and greater presence of minerals from the feldspar group for samples from 8 and 3. The main silicate is quartz, which is found with inclusions of Au, mainly for deposits 4, 8 and 3 (Fig 4). The differences between the types of sulfides and associations with Au mark the main mineralogical difference between the structures. While berthierite/arsenopyrite is the main source of S in deposit 6, pyrrhotite/

pyrite/arsenopyrite are abundant in the structures of 4, 1, and 2. In these sulfides, the presence of attached and included Au has also been described (Fig 4).

For dam 6, oxides and jarosite containing high Sb concentration are also observed. This fact also shows that these minerals are distinct from other deposits. The presence of a high content of oxides and jarosite in the rejects of 5 and 6 is due to the transformation steps in a roaster and autoclave for Au extraction in metallurgical plants (Lemos *et al.*, 2019). The other deposits have minerals that are more common among themselves because they receive wastes from the flotation stage, which has a low degree of mineral transformation (Lemos *et al.*, 2019).

Table 2 Mineralogy of tailings deposits 1 to 8 obtained by FEI microscopy analysis.

Minerals/compounds	Chemical Formula	1	2	3	4	5	6	7	8
		Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %
Quartz	SiO ₂	36.65	31.57	37.83	55.8	15.6	35.6	34.18	42.83
Albite	NaAlSi ₃ O ₈	2.81	5.33	7.56	0.37	1.5	1.11	0.07	8.95
Anorthite	CaAl ₂ Si ₂ O ₈	0.01	-	0.03	0.01	0.053	0.053	0.07	5.44
K-feldspar	KAlSi ₃ O ₈	1.22	0.12	0.73	0.39		1.27	1.18	0.52
Biotite	KMg _{2.5} Fe _{2+0.5} AlSi ₃ O ₁₀ (OH) _{1.75} F _{0.25}	0.52	0.11	2.55	0.16	1	1.26	1.74	8.30
Smectite	(Si,Al)(Mg,Fe)O(OH)NaH ₂ O	-	-	1.28	0.13	1.8	-	-	-
Muscovite Group	KAl ₂ Si ₄ O ₁₀ (OH) _{1.9} F _{0.1}	20.58	6.53	27.57	5.56	11	29	38.46	12.53
Chlorite	(Mg,Fe) ₃ (Si,Al) ₄ O ₁₀ (OH) ₂ ·(Mg,Fe) ₃ (OH) ₆	5.83	2.44	1.28	6.12	3.3	5.01	3.34	6.13
Iron Oxides/Hydroxides	Fe ₂ O ₃ /FeOOH	8.95	-	9.06	8.86	56.8	0.378	17.09	0.41
Fe antimoniate	FeSb(As)O	-	-	-	-	-	0.806	0.07	-
Rutile	TiO ₂	0.56	0.19	0.60	0.49	0.599	0.599	0.29	0.16
Ankerite	Ca(Fe,Mg,Mn)(CO ₃) ₂	0.85	16.84	1.49	11.2	1	9	0.02	6.49
Siderite	FeCO ₃	8.94	2.92	0.01	7.25	-	7.2	0.17	0.03
Dolomite	CaMg(CO ₃) ₂								2.10
Calcite	CaCO ₃	-	0.02	0.23	2.25	0.2	5.4	0.05	1.60
Jarosite (Sb)	KFe(SO ₄) ₂ (OH) ₆ & (H ₂ O)Fe(SO ₄) ₂ (OH) ₆	-	-	-	-	-	1.00	-	-
Gypsum	CaSO ₄ ·2H ₂ O	-	-	-	0.03	7	2.00	-	-
Pyrite	Fe ²⁺ S ₂	0.22	5.31	0.06	0.5	0.002	0.08	0.03	0.11
Pyrrhotite	Fe ^{2+0.95} S	4.7	2.06	0.148	0.79	0.004	0.041	-	1.803
Arsenopyrite	Fe ³⁺ AsS	1.71	2.52	0.022	0.24	0.056	0.056	-	0.389
Berthierite	FeSb ₂ S ₄						0.141	-	-
Chalcocopyrite	CuFe(S) ₂	0.21	0.01	-	-		0.028	-	0.05
Gesdorffite	NiAsS	-	0.02	-	-	0.01		-	-
Covellite	CuS	0.01		-	0.07	0.1		-	-
Sphalerite	ZnS			-	0.01	-	0.009	-	-
Native Gold*	Au > 80%, Ag, Cu, Hg	60	45	2	364	526	158	20	740
Electrum*	Au = 80%, Ag = 20%	5	8	1	10	42	6	5	19

* Number of Au particles

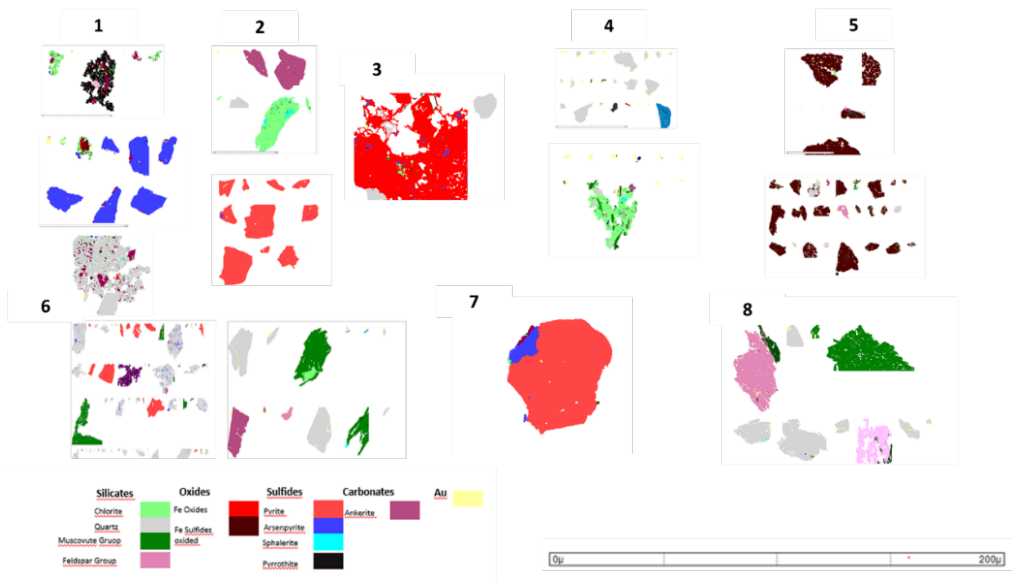


Figure 4 Electronic image in false color of minerals and Au association of the tailings deposits 1 to 8.

Conclusion

The results showed distinct characteristics between groups of samples from the tailings deposition structures.

Among the seven chemical variables, three distinct groups are identifying, being 1, represented by points close to the Au axis with most points of deposit 5. Group 2 is more close to the Sb axis with most points of deposits 6 and 7. Finally, there is a third group, with other deposits between the S, Fe and C axes.

The sources of S, Cu, and As are represented by sulfides and sulfates, the latter being mainly present in deposits 5 and 6. In the case of deposit 5, it can also be deduced, due to its genesis, that Fe oxides also carry these elements. C contents are related with carbonates, mainly in samples from deposit 2.

The characterization of tailings solids also revealed the levels and modes of occurrence of elements considered at risk of supply according to the European Commission's list, such as Au, Sb, and As. Jarosite and Fe antimoniate are relevant host phases.

All these chemical and mineralogical relationships demonstrate the need for separate storage and safe management in the handling and disposal of these products.

Even considering that these elements occur in complex forms the high concentrations of

Sb, As, and Au demonstrate their potential for reuse. Furthermore, studies should be made to convert these tailings into resources, proving that they could have interesting grades and, thus, aspirations in the context of the circular economy can be validated.

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