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GEOCHEMISTRY OF WASTE FROM THE TAILINGS POND OF PÂRÂUL CAILOR, FUNDU MOLDOVEI METALLOGENIC FIELD, ROMANIA

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Abstract: The waste of the tailings pond has a yellowish appearance, over 70-80 wt% consisting of fine and very fine particles. The dominant minerals are quartz, sericite, chlorite and pyrite, while sphalerite and biotite occur accidentally. Translucent crystal grains of presumed hydrated sulfates were identified as well. The pH is very low (mean of 3.1), as well as the abundance of the soluble fraction (mean less than 2.0wt%). Across the surface of the waste deposit, four sectors with specific geochemical properties were identified, using statistical analyses: (1) the northern and southern edges of the horizontal surface (C2), where the waste is the most susceptible to be removed and transported either by wind or by runoff; (2) the flat, horizontal sector C1, rich in Al, Mg, Mn, and K, where especially the silt and clay particles accumulate; (3) the sector C3 which overlaps the watercourse of the temporary stream, the latter being the main vector of mechanical and chemical removal and transport of waste towards the surrounding areas; (4) the sector C4, the richest in toxic trace elements, related especially to primary sulfides, less mobile because of their higher specific weight. The relation between this geochemical distribution and other properties of the tailings (e.g., mineralogy, grain size, abundance of soluble fraction, pH) suggested that the sectors C2 and C3 present the highest risk to the environment.

Keywords: Mine tailings, geochemistry, spatial distribution, statistical analysis, Fundu Moldovei

1. INTRODUCTION

Historical and present-day ore processing activities result in the accumulation of large quantities of waste, as tailing impoundments of different types (Hudson-Edwards et al., 2003; Kossoff et al., 2012), such as valley-cross or side-hill tailings dams (U.S. Environmental Protection Agency, 1994). During ore-processing operations, the tailing impoundments are usually covered by water. However, in the long run, the water evaporates, allowing the access of oxygen to primary minerals in the tailings ponds; this triggers weathering processes of high risk for the environment (Concas et al., 2006; Quispe et al., 2013).

Generally, mine tailings consist of sand to clay size particles of both silicate and metallic minerals, which result from the ore-processing activity (Forsberg & Ledin, 2006; Andrés & Francisco, 2008; Audry et al., 2010). Once exposed to weathering agents, the silicates and metallic minerals undergo alteration processes, this way some of the silicates being transformed into clay minerals (Bétard et al., 2009; Harraz & Hamdy, 2010). When exposed to atmospheric oxygen and water, sulfides (especially pyrite) are oxidized, producing acidic leachates with high contents of SO_4, Fe and other toxic and potentially toxic elements (e.g., Cu, Pb, Zn, Cd, As) (Álvarez-Valero et al., 2009; Yurkevich et al., 2012; Stevanovic et al., 2013). The highly acidic leachates are known as acid mine drainage (AMD) (Akcil & Koldas, 2006; Sracek et al., 2010; Martínez-Pagán et al., 2011) and in absence of a precautionary management, they may be discharged into the surrounding areas, e.g., bodies of surface waters (Gurzău et al., 2012).

An oxidation zone may also be formed immediately below the waste surface. The oxidation zone develops in depth, to the limit where the diffusion of oxygen from the surface occurs. Its thickness depends on the presence of coarse pores and subsequent low water saturation (Quispe et al., 2013); it is noticeably by the yellow-reddish color, given by Fe^{3+} coating of mineral particles and Fe^{3+}-rich hydrated oxides and sulfates. The secondary hydrated sulfates usually occur when tailings ponds are exposed to atmosphere for several years or during dry periods (Hammarstrom et al., 2005; Triantafyllidis & Skarpelis, 2006). They form through precipitation from the acid mine drainage and are highly variable in solubility: highly soluble Fe sulfates (e.g., melanterite); less soluble Fe hydroxysulfates (e.g., jarosite); relatively insoluble sulfates (e.g., anglesite) (Yin & Catalan, 2003). Secondary hydrated sulfates can trap toxic and potentially toxic metals and release them by dissolution, during rainfall.

This paper consists in a geochemical characterization of the upper surface of the unconfined tailings pond of Pârâul Cailor. It lies on the distribution analysis of some major and toxic elements across the surface of the waste deposit and its relation with the mineralogy, grain size, soluble fraction abundance and acidity of the tailings.

2. GEOLOGY AND STUDY AREA

2.1 Geological setting

The Polymetallic Mineralization Belt associated to the low-grade metamorphic rocks from Eastern Carpathians displays a NW-SE orientation and is settled in the Alpine Bucovinian Nappe (Berbeleac, 1988; Balintoni, 2010). This tectonic unit consists of Mesozoic sedimentary deposits and Precambrian-Cambrian metamorphic terranes; within the latter, many pre-Alpine tectonic units have been identified, i.e., Rodna Nappe, Pietrosul Bistriței Nappe, Putna Nappe and Rarău Nappe. The polymetallic sulfides in the Eastern Carpathians are associated with the metamorphic rocks of the Tulgheș Group, which is part of the Putna Nappe. The Group of Tulgheș, in turn, was divided in four sub-units, as follows: Căboaia, Holdița, Leșu Ursului and Arșița Rea. The polymetallic mineralization is hosted by the Leșu Ursului sub-unit, which is a metamorphosed volcano-sedimentary sequence (Balintoni, 2010).

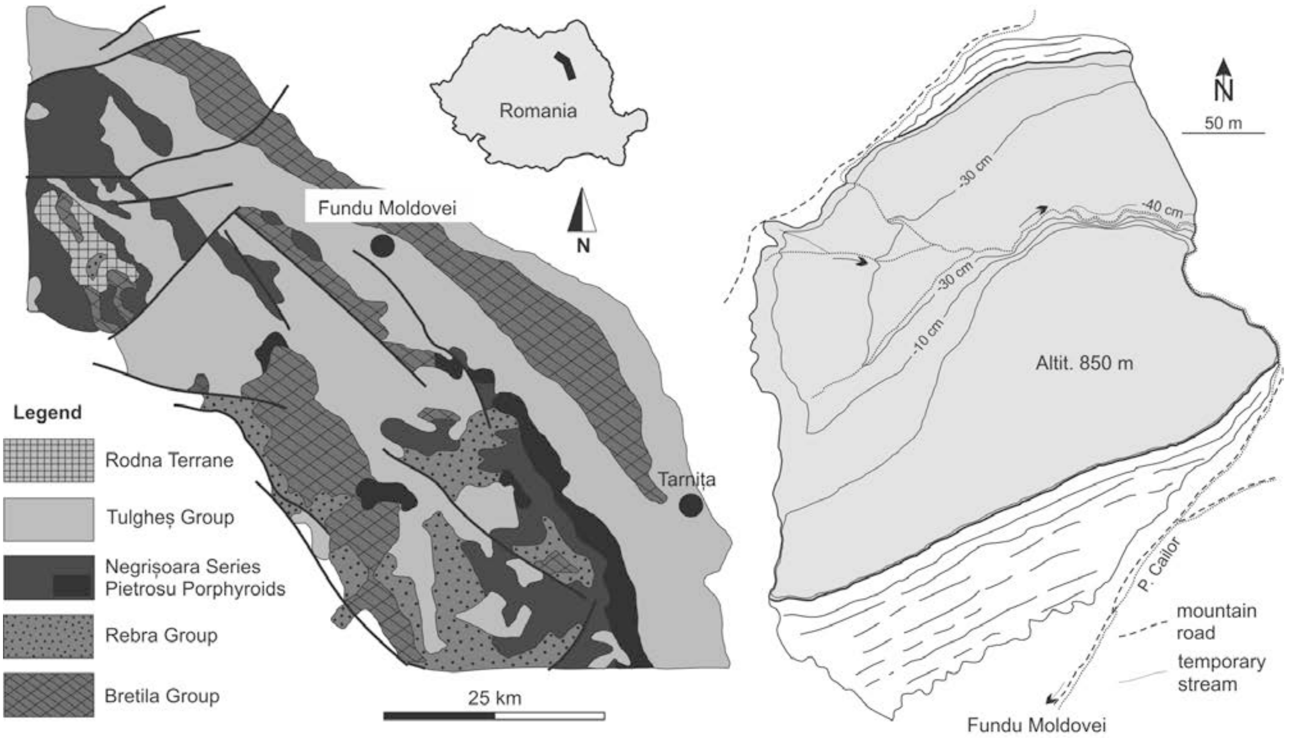
Tulgheș Group is a low-grade metamorphic unit, which have gone through Caledonian and Variscan polymetamorphic events. The lithology is varied, being especially dominated by quartzites and quartz-feldspar rocks. However, the continuous variation of the ratio between quartz, feldspars, chlorite and sericite results in a complicated lithology. In the Polymetallic Belt of the Eastern Carpathians, three metallogenic districts were identified (Berbeleac, 1988); from NW to SE, they are: (i) Borșa-Vișeu; (ii) Fundu Moldovei-Leșu Ursului (Fig. 1a); and (iii) Bălan-Fagu Cetății. The perimeter under study is located in the Fundu Moldovei-Leșu Ursului Metallogenic District, more precisely the Fundu Moldovei Metallogenic Field. In this metallogenic unit, the sulfide mineralization appears as massive or disseminated ores, which consist mostly of Cu-rich pyrite and, occasionally, chalcopyrite. As accessory minerals, sphalerite, galena, arsenopyrite, tetrahedrite and bismuthite were recorded. Within the upper level of the metallogenic sequence, sphalerite and galena prevail over pyrite.

2.2 Site description

The tailings pond under study was built up in the upper course of the Pârâul Cailor creek, at around 2.5 km NE from its confluence with the Moldova River; about 600 m downstream from the tailings impoundment, a limestone quarry is operating. The waste pond is a valley-type impoundment and it was accumulating the slurry from the ore preparation plant of Fundu Moldovei, which has ended the activity in 2004. The tailings dam is 30 m high and contains about 0.90 M m^3 of waste. The upper, horizontal surface is 350 m long and 280 m wide. The southern flank is heavily deteriorated by rain water flows, which has produced erosion gullies, leading to the removal and transport of the waste towards the bottom of the slope. The northern flank is only 7-8 m high and it is also affected by erosion.

The limit between the horizontal surface of the tailings pond and the two flanks is given by 80-100 cm high ridges. Generally, the waste deposit has a yellowish appearance. However, the horizontal surface is grayish, while the flanks are deep-yellow to ochre. The northern sector of the horizontal surface of the tailings pond is about 40 cm lower than the rest of the waste surface. It is crossed from west to east by a temporary stream which removes and transports the tailings during heavy rains (Fig. 1b). The northern flank of the stream has a much smaller slope than the northern one. During rainy periods, the stream seems to act as a collector of detritus transported by the surface runoff. South from the temporary creek, the waste deposit forms a plateau. Generally, the tailings have a highly variable texture, the grain size ranging from medium sand to silty or even clayey particles.

In the area, the weather displays parameters specific to the low-altitude mountain regions (850 m altitude) in temperate climate zone. Thus, the average summer temperature of air is about 16ºC and the humidity is over 80%. The rainfall regime of 83 mm/year is rather moderate for a mountain area, while the wind blows mostly from NW, having an average speed of 4.3 m/s.



(a) (b)

Figure 1. (a) Geological map of the Fundu Moldovei – Leșu Ursului Metallogenic District (Balintoni, 2010, modified); (b) Sketch of the tailings pond of Pârâul Cailor.

3. METHODS

3.1 Sampling

The field survey was carried out during the autumn of 2013, when 30 samples of tailings have been collected from the upper, horizontal surface of the waste deposit, on a rectangular grid of 50 × 30 m. The waste was sampled from the surface of the tailings pond, with help of a plastic paddle. Then, the samples were stored in plastic bags until being analyzed.

3.2 Analyses

3.2.1. Microscopic determination

The mineralogical composition of tailings was determined using a Meiji 9400 ML stereomicroscope. The method only helped to identify the primary minerals, such as quartz, sericite, chlorite, pyrite, and sphalerite.

3.2.2. Particle size analysis

The particle size analysis was carried out by performing the sieving method. To this purpose, the samples were first dried for 24h, at 50ºC, and then weighed. Next, the samples were passed through a set of sieves of known size, as follows: 1 mm, 0.25 mm, and 0.063 mm. In the end, the weight percent for three grain size classes was calculated: medium sand, fine + very fine sand, and silt + clay.

3.2.3. X-ray fluorescence

To determine de abundance of the major and toxic elements in the tailings, the energy-dispersive X-ray fluorescence (EDXRF) has been used; the measurements were carried out with help of an Epsylon 5 XRF-spectrometer. Prior to analysis, the samples were ground and mixed with Hoechst wax, then pressed to pellets. The calibration of the spectrometer was based on data for lake and river sediments, as reference materials.

3.2.4. Leaching tests

The soluble fraction and pH were determined by mean of leaching tests. To this purpose, a 10 g tailing aliquot was mixed with 100 mL of deionized water (pH about 6) and shaken for 1 h at 200 rpm. Then, the leachate was filtered through a 0.2-μm cellulose filter and the pH was measured immediately using a Corning M555 pH/ion meter. The insoluble fraction resting on the cellulose filter was dried and weighed to calculate the percentage of soluble phase.

3.2.5. Statistical analysis

To determine some statistical parameters and perform cluster analyses and Factor Analysis, the XL Stat Pro 7.5 software has been used.

4. RESULTS AND DISCUSSION

4.1 Tailings description

The waste from the tailings pond generally displays a sandy appearance. In the southern sector, the detritus present a more intense yellow color and a silty to clayey particle size. The grain size data are summarized in table 1, showing that up to 70-80 wt% of the waste consist of fine and very fine particles.

Table 1. Grain size analysis (wt%) of the tailings (*n* = 20)

	Medium sand	Fine and very fine sand	Silt + Clay
Min.	0.23	26.91	10.89
Max.	16.09	80.69	72.09
Mean	4.85	57.02	38.13
SD	2.89	19.48	23.70

SD-standard deviation

The distribution map for the grain size of the tailings (Fig. 2a) reveals a close relation between this parameter and the morphology of the upper surface of the waste deposit. Thus, the tailings from the 70-80 cm high ridges that border the tailings pond at north and south (C2 in Figure 2a) consist of the largest particles in the waste, i.e., medium size sand. Due to their shape, the ridges are the most exposed to climate agents, hence the most susceptible to tailings removal by wind and water runoff during rainfalls. As a result, it is expected that the smallest particles (i.e., silt and clay size waste) were transported in the nearby, horizontal area (C1). Besides, the map in Figure 2a shows that in this latter area was accumulated the largest amount of silt and clay size tailings. The northern sector of the tailings pond surface (C3, C4) is the area from which the temporary creek that crosses the waste deposit (Fig. 1b) collects the detritus during the rainy periods.

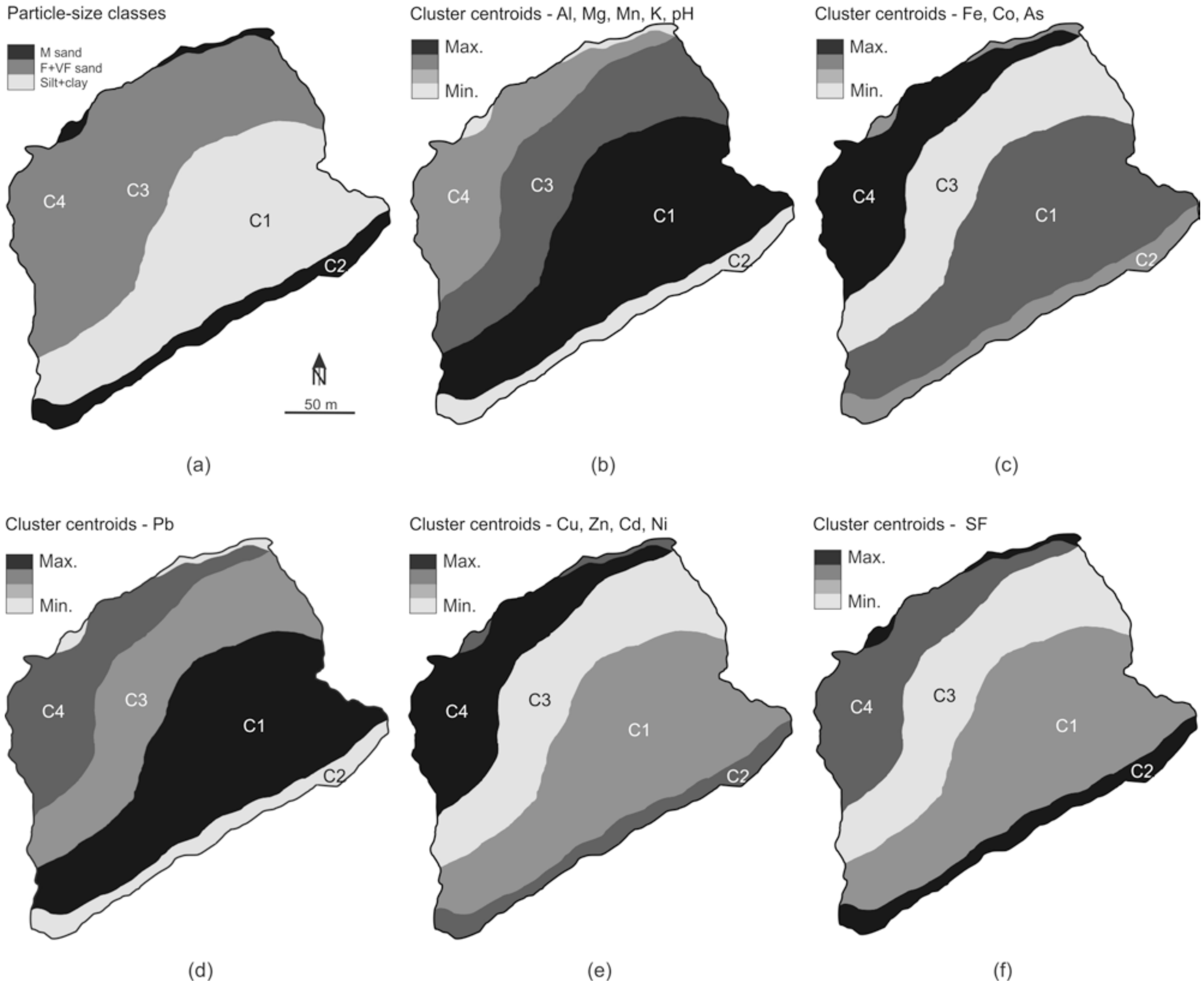


Figure 2. The variation of cluster centroids and particle-size classes across the surface of the tailings pond. M – medium; F+VF – fine and very fine; SF – soluble fraction.

This sector is less exposed to wind, so the tailings removal is almost exclusively done by water runoff. The latter process can lead to the removal of the largest waste particles, which explain their lower abundance in this sector (C3, C4).

The microscopic observation of primary minerals was carried out after a prior rinsing of sample with deionized water. The procedure was performed to remove the highly soluble mineral fraction which makes difficult the identification of primary mineral species. The microscopic observations show a large abundance of quartz and sericite; frequently, quartz displays a limonite coating. Chlorite was also usually identified, while some samples display a high abundance of pyrite. Sphalerite and biotite occur accidentally. The unrinsed samples show small aggregates of translucent crystal grains, presumed to be hydrated sulfates, as showed by previous studies on similar tailings in Eastern Carpathians (Stumbea, 2013a,b).

Table 2. pH and amount of soluble fraction of the tailings (*n* = 30)

	pH	Soluble fraction (wt%)
Minimum	2.63	0.45
Maximum	3.90	5.12
Mean	3.13	1.93
SD	0.43	1.24

4.2 Geochemistry

Data on pH are summarized in table 2, showing the high acidity of the tailings. The low pH is generated by the long-term pyrite oxidation within the tailings, which result in highly acidic pore water that contains metals and SO_4 (Moncur et al., 2005; Graupner et al., 2007). The abundance of the soluble fraction is less than 5 wt%, which is relatively low in comparison with other occurrences (Stumbea, 2013a,b). The appearance of the soluble fraction is closely related to the exposure of sulfide-bearing tailings to air and water (Hesketh et al., 2010; Parviainen et al., 2012). This results in highly acidic leachates, which can be accumulated in shallow pools, where they evaporate and produce hydrated oxides and sulfates aggregates of Al, Fe, Mg and Mn. The latter may also occur as crusts on the tailings surface, as a result of evaporation of the acidic pore water.

The contents of major and toxic elements are summarized in table 3. The chemical properties reflect the mineralogy of the tailings, dominated by the primary minerals. Thus, the relatively high amounts of Al, Fe, Mg and K are related especially to chlorite, sericite, biotite and pyrite. However, these elements can also be found in secondary hydrated oxides and sulfates that can occur during the dry periods of time (Tutu et al., 2008; Sherriff et al., 2011). The most abundant elements in the tailings under study is silicon (not shown in Table 3), its content ranging between 53 and 79 wt%. It comes from the already mentioned silicates, but mostly from quartz which is present in large quantities in the tailings. The most abundant toxic and potentially toxic elements are Pb, Cu, Zn and As (Table 3); these elements come from the primary sulfides (pyrite, sphalerite), but they can also be incorporated within the secondary hydrated sulfates (Romero et al., 2007; Sidenko et al., 2007; Corriveau et al., 2011).

4.3 Statistic analyses

The high value of Pearson correlation coefficient between Al, Mg and K (Table 4) is explained by their association in the primary minerals of the tailings (e.g., chlorite, sericite, biotite) and the secondary as well (i.e., the presumed hydrated oxides and sulfates). Most likely, the very strong positive correlation between Fe and Co (0.99) is due to the presence of these two elements in pyrite, which is abundant in some of the tailings pond areas. The correlation coefficient shows a relatively strong relation of Cu with Zn and Cd, as well as a very strong positive correlation (0.97) between Zn and Cd. The latter is due to the general affinity between the two elements.

Table 3. Average contents of major and toxic elements in tailings sample (*n* = 30)

	Al	Fe	Mn	Mg	K	Co	Ni	Cu	Zn	Pb	As	Cd
	(wt%)						(ppm)					
Min.	2.58	4.22	0.02	1.52	0.76	17	1.53	151	80	471	74	0.02
Max.	19.33	11.80	0.04	5.21	4.68	60	6.20	1982	1112	2504	304	0.52
Mean	9.85	7.89	0.03	3.21	2.49	38	3.41	615	222	1204	155	0.10
SD	4.99	2.03	0.01	1.06	1.09	12	1.03	523	206	517	54	0.10

Table 4. Pearson correlation coefficient

	Al	Fe	Mn	Mg	K	Co	Ni	Cu	Zn	Pb	As
Al	1.000										
Fe	0.269	1.000									
Mn	**0.530**	-0.008	1.000								
Mg	**0.769**	0.201	**0.509**	1.000							
K	**0.976**	0.171	**0.489**	**0.770**	1.000						
Co	0.215	**0.994**	-0.083	0.153	0.118	1.000					
Ni	-0.145	0.102	-0.191	-0.320	-0.158	0.102	1.000				
Cu	-0.320	0.339	**-0.780**	-0.307	-0.295	**0.410**	0.241	1.000			
Zn	-0.105	**0.376**	**-0.559**	-0.085	-0.111	**0.434**	-0.110	**0.747**	1.000		
Pb	**0.368**	**0.521**	-0.064	0.266	**0.392**	**0.510**	-0.076	0.307	**0.421**	1.000	
As	0.278	**0.770**	-0.015	0.185	0.252	**0.753**	0.137	0.276	0.287	**0.687**	1.000
Cd	-0.142	0.324	**-0.659**	-0.167	-0.144	**0.386**	0.000	**0.797**	**0.976**	**0.397**	0.283

In bold, significant values at the level of significance alpha=0.05

Table 5. Cluster centroids of the tailings

Cluster	Al	Fe	Mn	Mg	K	Co	Ni	Cu	Zn	Pb	As	Cd
	(wt%)					(ppm)						
C1	15.06	8.98	0.03	4.31	3.64	43	3.20	334	166	1446	187	0.06
C2	4.07	6.48	0.02	2.19	1.35	31	3.41	761	168	940	122	0.08
C3	11.89	6.00	0.03	3.65	2.94	27	3.15	329	131	941	100	0.05
C4	7.52	9.29	0.02	2.54	1.84	47	3.85	1016	401	1360	188	0.19

The k-mean cluster analysis of the geochemical data shows four groups of data, whose centroids are presented in table 5. The distribution maps of the four clusters on the surface of the tailings pond under study are presented in Figures 1b-f. The shape of the distribution sectors should be considered with the morphology of the upper surface of the tailings pond. Thus, cluster C2 overlaps the 80-100 cm high ridges which outline the surface of the waste deposit at south-east and north-west. The cluster C1 gathers the samples from the flat, horizontal surface of the southern sector of the tailings pond. The clusters C3 and C4 overlaps the northern sector of the waste deposit, where the temporary stream collects the tailings during heavy rains; the surface of C4 superpose on the slightly elevated part of this small water collection pool. Figure 1a only uses the shape of the four clusters to point out the variation of the tailing particle size over the surface of the waste deposit. To simplify the discussion, the four sectors of the tailings pond will be named as C1, C2, C3, and C4.

The southern and northern edges of the tailings pond (C2) consist of the largest particles (medium sand size tailings) and have the highest amount of soluble fraction (Fig. 1a,f). This may be explained by the removal of the smaller particles (fine sand, silt and clay size tailings) by wind and surface runoff during rainfalls. After removal, the fine particles may be transported and accumulated onto the flat, horizontal sector C1. The tailings of C2 are the most exposed to wind and therefore to drying processes which may result in the formation of highly soluble hydrated sulfates. This explains the high abundance of soluble fraction determined in the tailings from the C2 sector, during dry periods (Fig. 2f).

The tailings of the sector C1 have the highest amounts of Al, Mg, Mn, and K (Fig. 2b) relative to the others three sectors of the waste deposit. This enrichment may be attributed to a high abundance in primary silicates (chlorite, sericite) or secondary hydrated sulfates. The latter may accumulate in the C1 sector for the following reasons: (i) the flat surface allows the evaporation of the acidic water pores and the appearance of hydrated oxides and sulfates; (ii) due to the flat shape and the large extent of the C1 sector, most of the leachates formed by dissolution of sulfates accumulate on the same surface, as shallow pools. The latter process is confirmed by the high abundance of the silty and clayey size tailings in this sector (Fig. 2a).

The sector C3 displays a relative high amounts of Al, Mg, Mn, and K (Fig. 2b), but the lowest abundance of toxic elements (Fig. 2c,e) and soluble fraction (Fig. 2f). As the C3 sector overlaps the area of the stream watercourse, these geochemical properties may be explained by the removal of highly soluble hydrated sulfates, which usually trap the toxic and potentially toxic elements. Furthermore, the sector seems to be rich in primary silicates (chlorite, sericite) as the high contents of Al, Mg and K suggest. The abundance of silicates is due to their preferential removal and transport from the C4 sector, during rainfalls, as a result of their lower specific weight, compared with the sulfides. The low contents of most of the toxic elements (Fig. 2c,e) is explained as follows: (i) the abundance of silicates, which have low amounts of toxic elements; (ii) the low content of soluble fraction, i.e., hydrated sulfates, known as traps of the toxic elements.

The largest amounts of toxic trace elements are accumulated within the tailings of the sector C4 (Fig. 2 c,e). The abundance of toxic elements is due, partly, to sulfides (especially pyrite, accidentally sphalerite), which were not transported towards the sector C3 because of their high specific weight. The presence of toxic elements within the tailings of sector 4 may also be related to the relative high amount of soluble fraction (hydrated sulfates) (Fig. 2f).

The factors that determine the variation of geochemical properties across the surface of the tailings pond were identified using the Factor Analysis (FA). The results are summarized in the Table 6, where data are grouped in a two-factor model, accounting for 70.60% of all data variation. The diagram in figure 3 shows the plot of F1 and F2 factors against each other.

Factor F1 seems to reflect the influence of the type of primary mineral (i.e., silicate or sulfide) on the chemical properties of tailings. Thus, the negative values of F1 refer to major elements coming from schist silicates, which formed through endogenous processes (i.e., chlorite, sericite, accidentally biotite). In terms of their distribution on the surface of the waste deposit, these elements mostly occur within the tailings from the sectors C1 and C3. F1 is positive when it controls the properties of the elements derived from the primary metallic minerals, such as pyrite, sphalerite and much less abundant galena. These latter elements (i.e., Fe, Pb, Co, As, Zn, Cd) are toxic and potentially toxic, the highest abundance being recorded in the sector C4 of the waste deposit.

Table 6 Factor analysis: factor loadings

Variable	F1	F2	Communality
Si	0.263	-0.619	0.898
Ti	-0.154	0.103	0.642
Al	-0.466	0.801	0.991
Fe	0.493	0.699	0.998
Mn	-0.737	0.333	0.900
Mg	-0.467	0.699	0.882
Ca	-0.270	-0.045	0.727
Na	-0.332	0.219	0.646
K	-0.482	0.758	0.987
P	0.361	-0.085	0.900
Co	0.556	0.654	0.998
Ni	0.191	-0.085	0.706
Cu	0.849	0.006	0.919
Zn	0.785	0.248	0.988
Pb	0.333	0.670	0.829
As	0.383	0.653	0.870
Cd	0.825	0.186	0.991
FS	0.264	0.300	0.655
pH	-0.048	0.344	0.683
Eigenvalue	4.552	4.370	
% variance	36.020	34.580	
% cumulative	36.020	70.600	

SF – soluble fraction (wt%)

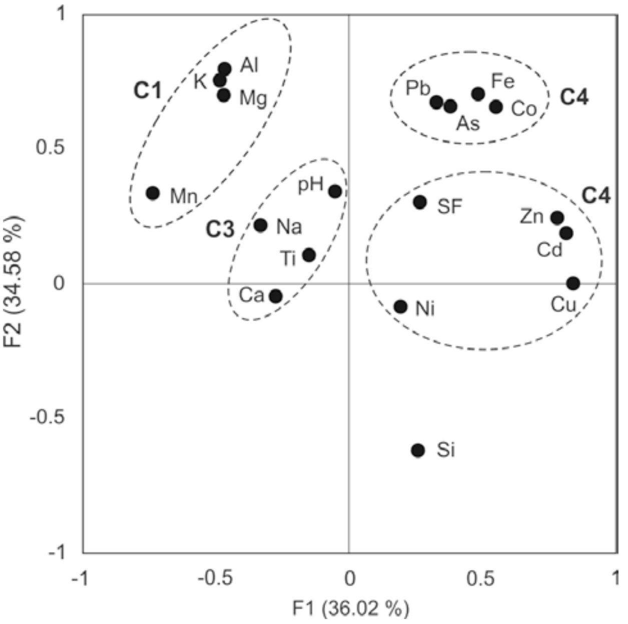


Figure 3 Factor loading plots for Factor Analysis. SF-soluble fraction.

The factor F2 may be associated with the extent to which the processes of weathering influence the distribution of both pre-existing silicates and metallic minerals in tailings. Therefore, the lower half of the diagram in figure 3 indicates the elements completely or almost completely inert (Si, Ni) in terms of involvement in weathering. The upper half of the diagrams (positive F2) may refer to geochemical properties influenced by the weathering of the tailings. Thus, the distribution of Mn, Na, Zn, Cd and also the pH and abundance of the soluble fraction are influenced by moderate intensities of weathering (F2 less than 0.5). Over time, the weathering becomes increasingly intense, as a result of the recurrence of cycles oxidation-hydration-dehydration. In figure 3, the increasing weathering is represented by F2 more than 0.5; the elements affected by this process are Al, Mg, K (originated in primary silicates) and Fe, Pb, As, Co (coming from the primary sulfides).

5. CONCLUSIONS

The geochemical properties and the preliminary mineralogical composition of the waste from the upper, horizontal surface of the tailings pond under study suggest four main patterns. They seem to be related to the waste mineralogy, morphology of the surface of waste deposit and tailings exposure to climatic agents.

The edges which outline the horizontal surface of the waste deposit at south-east and north-west (sector C1) are the most susceptible to tailings removal and transport either by wind or runoff during rainfalls. This assumption is supported by the abundance of coarse tailings in these edges, as a result of removal of fine particles towards the surrounding areas. This also explains the highest amount of silt and clay particles recorded within the closest northern sector (C1).

The waste of the sector C1 is the richest in major (Fe, Al, Mg, Mn, K) and some of the minor toxic elements (As, Co, Pb). It also is susceptible to accumulate hydrated oxides and sulfates, while the risk of toxic matter removal is the lowest of the tailings pond. This is because both its large horizontal surface and the southern edge of the waste deposit prevent the removal of tailings by water runoff. Moreover, being a cross-valley tailings pond, the more is the sector located to north, the more is spared from wind action; consequently, the C1 sector is less exposed to wind than sector C2.

The sector C3 mainly overlaps the watercourse of the temporary stream that flows from west, to east. This stream removes and transports the tailings of the area it crosses, fact that explains the low abundance of soluble fraction. Besides, during moderate to heavy rainfalls, in the stream watercourse area is collected waste brought by runoff from the sector C4, located immediately north of C3. The tailing accumulated this way contains high amounts of elements coming from primary silicates (Al, Mg, Mn, and K) and shows the lowest contents of toxic elements. These features suggest the preferential removal and transport of the much lighter silicates, at the expense of metallic minerals, from the sector C4 towards C3.

An overview on the results of the study suggests that the tailings develop two type of environmental risk: (i) an immediate risk, as is the case of sectors C2 and C3, where the waste is transported towards the surrounding areas when moderate to heavy rains occur: (ii) a potential risk (sectors C1 and C4), expressed by the low pH of the tailings and their generally high amount of toxic elements.

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