

THE FLANKS OF THE DEALUL NEGRU TAILINGS POND (FUNDU MOLDOVEI) – POLLUTION RISK FACTORS

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Abstract: The study focuses on identifying the risk factors for the environmental pollution generated by the flanks of the tailings pond of Dealul Negru (Fundu Moldovei mine district); in this purpose, textural, mineralogical, geochemical and statistical analyses have been carried out. XRD patterns allowed to identify two groups of minerals: primary minerals (especially chlorite, muscovite, biotite, quartz), and weathering minerals; the latter group consists of clay minerals (illite and kaolinite) and highly soluble hydrated sulfates (especially gypsum and apjohnite, but also pickeringite, halotrichite, jarosite). The main feature of the tailings is the differences identified between the waste from the upper levels and lower levels of the tailings pond, as follow: (1) a larger abundance of coarse waste particles (about 12 wt%), higher abundance of soluble fraction (mean of 0.63 wt%) and higher amounts of Fe and S (major elements), and Zn, Cu, Pb, Cd, Cr, As (toxic elements) within the waste from the upper levels; (2) an increasing abundance of the fine and very fine waste particles (up to about 80 wt%) and higher pH (up to 3.75) specific to the tailings from the lower levels of the waste deposit. On the contrary, the Principal Component Analysis suggests that the key role in unfolding these geochemical patterns is rather played by the waste cemented layers developed on the surface of the lower levels of the waste deposit. However, the upper levels are the most susceptible to trigger environmental pollution, especially through surface runoffs during heavy rains and wind-driven removal and transport; the upper levels also act as a source of “primary” waste for the lower levels of the waste deposit.

Keywords: Acid mine drainage; Tailings; Hydrated sulfates; Cemented layers; Toxic elements

1. INTRODUCTION

The processing of the sulfide ores results in tailings impoundments, generally abandoned when mining and extraction activities cease in a certain area; once exposed to the atmosphere for several years, the tailings dams become important concerns in terms of environmental pollution (Yin & Catalan, 2003; Concas et al., 2006). The concerns are even greater while the tailings ponds are vulnerable retention structures as result of their unstable nature, location near rivers and generally poor or nonexistent maintenance (Álvarez-Valero et al., 2009; Stumbea, 2013).

The main feature of the tailings pond, which triggers the process of environment contamination, is the sulfides remained within the waste, after the ore processing procedures. In the presence of oxygen and water, the sulfides (especially pyrite, but also chalcopyrite, sphalerite and galena to a certain

extent) undergo oxidation and become major risk factors for the acid mine drainage processes (Balistrieri et al., 2007; Sima et al., 2011). The latter may lead to the solubilization and subsequent release of toxic and potentially toxic metals such as Cu, Pb, Zn, Cd, As etc. (Andraš et al., 2009; Dimitrova & Yanful, 2012; Redwan et al., 2012; Stevanovic et al., 2013). Another environmental concern is the waste particle size, which makes the tailings highly vulnerable to removal and transport by surface runoff during heavy rains and wind (airborne transport) (Werner et al., 2001; Navarro et al., 2004). The wind transport increases the risk of human exposure to heavy metals by acting on the efflorescent salts (hydrated sulfates), developed at the surface of the tailings ponds; the efflorescent salts form through evaporation, which concentrates mobile elements, especially toxic metals (Smuda et al., 2008; Bea et al., 2010).

The oxidation and cementation processes may lead to the formation of cemented layers or even hardpans (Moncur et al., 2005; Lottermoser & Ashley, 2006; Graupner et al., 2007). The cemented layers are considered as early stages in hardpan development; they form through the agglutination of solid weathering products and display low porosity (Graupner et al., 2007; Redwan et al., 2012).

Starting from the knowledge outlined above, the aim of the present paper was to identify the various factors that may control the environmental pollution in the area of the Dealul Negru tailings pond (ore-processing plant of Fundu Moldovei). In this respect, the study focuses on the waste from the flanks of the tailings pond and deals with aspects such as: (1) the characterization of the textural, mineralogical and geochemical properties of the waste and their changes across the vertical plane of the waste deposit; (2) the identification of the most susceptible areas of the tailings pond to release hazardous solids and leachates into the surrounding areas; (3) the identification of the most common mechanism of pollution.

2. GEOLOGY AND STUDY AREA

2.1. Geological setting

The tailings pond of Dealul Negru is built up of waste resulted from the processing plant of Fundu Moldovei, which was extracting Cu from the polymetallic ores of the area. The ore bodies in the area belong to the Cu-rich Polymetallic Belt of the Eastern Carpathians, having a length of about 200 km and displaying a NNW-SSE direction. The mineralization is hosted by the rocks of the low-grade metamorphic Group of Tulgheș, which consists mostly of quartz-schists, sericite-schists and chlorite-schists (Berbeleac, 1988; Balintoni et al., 2009). Five units were identified within the Tulgheș Group, namely Tg1-Tg5, the richest in polymetallic mineralizations being the Tg3 unit; the latter is described as a volcano-sedimentary unit, consisting mainly of quartz-chlorite schists, sericite-quartz and sericite-chlorite schists, and rhyolitic metatuffs (Berbeleac, 1988). The polymetallic ores were concentrated in three metallogenic districts, as follow (from NNW to SSE): (1) Borșa-Vișeu; (2) Fundu Moldovei-Leșu Ursului (Fig. 1a); and (3) Bălan-Fagu Cetății (Berbeleac, 1988).

The ore deposits consist of sulfides and appear as massive strata, lenses or tabular bodies of disseminated metallic minerals. The most common sulfide is the Cu-rich pyrite, which is associated with chalcopyrite, sphalerite, and galena. Within the

metallogenic field of Fundu Moldovei (Fundu Moldovei-Leșu Ursului district), chalcopyrite dominates, in terms of quantity, sphalerite and galena; as all along the polymetallic belt, Cu was extracted from Cu-rich pyrite and chalcopyrite in the Fundu Moldovei perimeter. Pyrite appears as submillimetric crystals within the massive ores, while within the disseminated ore it has a millimetric size. Because its lower abundance compared with pyrite, chalcopyrite was considered a secondary raw mineral; it appears associated with pyrite, as either irregular appearances or millimetric veinlets. However, for economic reasons, the mining and processing activities in the Fundu Moldovei field ceased at the beginning of the first decade of the present century.

2.2. Location and description of site

The tailings pond of Dealul Negru lies on the right bank of Moldova River, at 1.5 km west from the village of Fundu Moldovei (Suceava County) (Fig. 1b). It spreads across about five hectares and is built up of 9-10 levels of about 3 m high each (Fig. 1c). The top of the waste deposit consists in a flat surface of 200 × 120 m. The tailings pond was collecting the waste resulted from the ore processing within the preparation plant of Fundu Moldovei, which ceased its activity in the early 2000s (Stumbea, 2012).

The tailings pond of Dealul Negru was built up as a valley impoundment of side hill type. The flanks of the waste deposit face north and north-west, and display a slope steepness of more than 45 degrees. Measures to reduce the tailings release into the nearby areas, especially into the Moldova River, were focused especially on the increase of the dam slope stability: construction of wooden retaining walls and tree planting on the lower, flatter, steps of the tailings pond. However, on-site survey of the waste deposit showed the limited efficiency of these measures, as proved by: the large number of erosion gullies developed especially on the slopes of the upper levels; the release of red-colored leachates (acid mine drainage) into the river bed of Moldova river; the movement of the tailings from the lower levels towards the river bed.

The perimeter under study has a climate specific to low mountains (750 m altitude) from temperate regions, with an average annual precipitation of 83 mm and an average air temperature during summer of 15.7°C. The humidity of air is 78% in average during the warm season and the wind blows mostly from NW, with an average speed of 4.3 m/s.

3. MATERIALS AND METHODS

3.1. Sampling

The tailings samples were collected using a plastic paddle, and then stored in plastic bags until being analyzed; the sampling points followed a rectangular sampling grid of 30×8 m, across the northern and western flanks of the tailings pond.

3.2. Analytical techniques

The microscopical investigation of the tailings, using a Meiji 9400 ML stereomicroscope, allowed a detailed description of samples and provided preliminaries on the waste mineralogy.

The particle-size analyses were carried out using the sieving method, after a previous dry of samples for 24h, in an air oven, at 50°C . Afterwards, the samples were weight and passed through the sieves of 1 mm, 0.5 mm and 0.063mm, to separate the following grain-size classes: coarse sand,

medium-coarse sand, fine and very fine sand, and silt + clay fractions. After the weight of each fraction, the percentage of the four classes was calculated.

In order to perform XRD analyses, the tailings were previously grounded, using a mechanic mill and an agate mortar. Afterwards, the samples were analyzed with help of a PW 1739 X-ray diffractometer, equipped with monochromatic $\text{CuK}\alpha$ ($\lambda=1.54056 \text{ \AA}$). Power settings were 40 kV and 25 mA, and the scan setting were $5\text{--}65^\circ 2\theta$, 0.5° step size, 2 s count time per step. Finally, the Rietica 1.77 software was used to perform a Rietveld structure refinement.

The chemical composition of tailings was determined by energy-dispersive X-ray fluorescence (EDXRF). In this respect, an Epsilon 5 XRF-spectrometer was used, after a previous ground of the samples and their mix with Hoechst wax. The spectrometer calibration was performed using data for river sediments as reference materials.

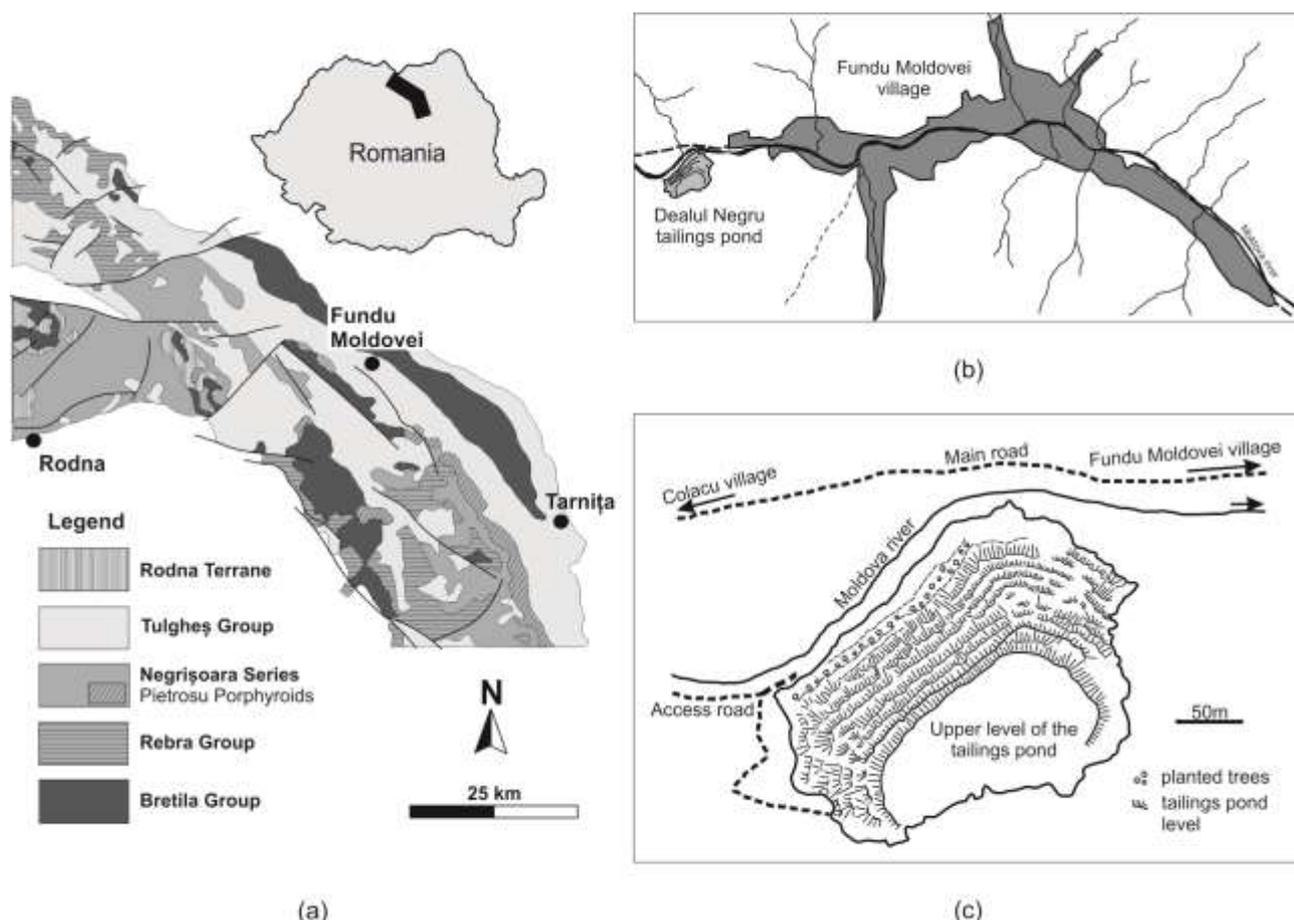


Figure 1. The geological setting and location of the Dealul Negru tailings pond. (a) Map of the Fundu Moldovei - Leșu Ursului metallogenic district (modified from Balintoni et al., 2009); (b) Location of the tailings pond relative to the Fundu Moldovei village; (c) Details of the Dealul Negru tailings pond.

The pH and abundance of the water soluble fraction were determined based on leaching tests. In this regard, each sample was dried at less than 50°C, then 10 g aliquot was mixed with 100 mL of deionized water (pH about 6); the beaker was then stirred for 2 h at 100 rpm. The pH of leachates was determined using a Corning M555 pH-meter, after a previous 2h decantation. Then, the leachate was filtered through a 0.2µm cellulose filter; the insoluble fraction resting on the cellulose filter was dried and then weighed to calculate the proportion of soluble phases.

The chemical data of the tailings also underwent statistical analyses, performed with help of the XL Stat Pro 7.5 software.

4. RESULTS AND DISCUSSIONS

4.1. Tailings description

The waste from the tailings pond of Dealul Negru has a yellow-ochre appearance, except for the lowermost 2-3 levels of the deposit, which display a dark-brown color; the appearance of the latter levels is given by the fine crusts (cemented layers) that cover the quasi-horizontal and the slightly sloping surfaces of the lowermost steps of the waste deposit. No obvious spatial relation was found between the development of crusts and the tree planted on the lower levels of the tailings pond.

In order to describe the tailings grain size, the terminology specific to the field of grain size analysis of sediments was used. Thus, the grain size analyses (Table 1) show that the tailings consists mostly of fine and very fine sand-size particles (roughly, 50% of the waste mass), silt and clay fractions (about one third of the waste mass). The changes of the fractions abundance across the vertical plane of the waste deposit are not significant (averages in Table 1), except for the (silt + clay) fraction, which displays a decrease of about 8% from top to bottom. As suggested by the ratios between the abundance of the (silt + clay) fraction and that of the other fractions, the decrease of the finest fraction at the bottom of the waste piles is related to an increase of coarser fractions, such as very coarse and medium-coarse sands (ratios in Table 1). This may suggest the tendency of accumulation of heavier, coarse fractions, at the lower levels of the tailings pond, due to their transport by water during heavy rainfalls. On the contrary, the finest fractions, much more susceptible to both airborne and water transport, are removed from the waste deposit. However, data in Table 1 show that, except for the medium coarse sand

particles, the standard deviation calculated for each fraction decreases from the upper levels of the tailings pond, towards the lowermost. This may suggest a homogenization of the solid material within the lower levels, as result of its redeposition after having been transported by either water or wind.

Table 1. Grain size analyses (wt %) of the waste from the tailings pond

	Very coarse sand	Medium coarse sand	Fine and very fine sand	Silt + Clay
Upper levels of the tailings pond (<i>n</i> = 16)				
Min.	0.01	0.98	16.65	3.67
Max.	8.75	14.18	68.28	48.75
Mean	2.96*	9.30	49.77	25.86
SD	3.97	4.56	16.92	16.45
Lower levels of the tailings pond (<i>n</i> = 19)				
Min.	0.00	2.90	43.87	20.32
Max.	6.70	14.98	65.96	45.32
Mean	2.36*	7.22	57.61	32.51
SD	2.86	4.84	8.90	10.16

SD-standard deviation; * geometric mean.

4.2. Tailings mineralogy

The microscopic examination of the tailings revealed two categories of minerals, as follow: (1) primary minerals that come from the low-grade metamorphic rocks and associated ores; (2) secondary minerals, formed on the account of the primary minerals, through weathering processes. The main primary minerals are quartz and chlorite, but also lower amounts of sericite, biotite and pyrite were identified. Under microscope, the secondary minerals mostly appear as needle-like, white, translucent crystals, on the surface of the primary minerals grains.

The mineralogical composition, based on X-ray diffraction of bulk samples, is shown in table 2; it confirms the primary mineral species identified by microscope and also gives detailed information about the secondary minerals. Thus, the latter consist of two categories: (1) clay minerals (especially kaolinite), formed through the weathering of the primary silicates; (2) hydrated oxides and sulfates resulting from the weathering of both primary sulfides and silicates. In terms of hydrated sulfates, the Rietveld refinement based on XRD data shows larger amounts of pickeringite, gypsum, coquimbite, jarosite, halotrichite and apjohnite. The semiquantitative data in table 2 may also suggest two mineralogical properties of the waste from

Dealul Negru: (1) a large number of hydrated sulfates species; (2) a large amount of hydrated oxides and sulfates, roughly ranging between 40 and 50% of the bulk sample. However, the number of mineral species and their abundance should be interpreted carefully, because of the 4-5 months delay between the sampling procedure and the XRD analyses. Consequently, the initial mineralogical composition of waste may have been enriched in some weathering minerals, during the storage in the laboratory (quaternary minerals, following the nomenclature of Jambor, 1994). An example of such a process may be coquimbite that displays an up to 7% abundance (Table 2); according to Jamieson et al. (2005), this mineral may form soon after sample collection or during the air drying procedures.

4.3. Geochemical properties of the tailings

The discussion on the geochemistry of the tailings is based on sample separation into two categories: (1) samples from the upper levels of the

tailings pond; (2) samples collected from the bottom of the waste deposit.

4.3.1 pH of the tailings

Data on pH of the tailings, from the upper and lower levels of the waste pond, are presented in table 3; the values point to highly acidic solids, with means of pH less than 4.0. The samples collected from the top display a lower pH (mean of 2.73), compared to tailings from the bottom (mean of 3.75); the increase of pH from top to bottom is of about 27%. A somehow similar pattern of pH data distribution on the surface of the Dealul Negru tailings pond has been identified by Balaban et al. (2011). The variation of pH suggests a higher susceptibility of the solids from the upper levels to release acidity into the environment. This environmental risk is amplified by the high exposure of the upper levels to both mechanical (wind- and water-driven transport) and chemical (leachates) removal.

Table 2. Mineralogical composition of tailings (semiquantitative % - Rietveld refinement based on XRD data)

	315	319	322	324	325	329	333	334	341
Primary minerals									
Chlorite	13	11	13	9	12	7	12	9	11
Sericite	7	5	6	5	6	3	6	5	6
Biotite	9	8	8	9	8	10	8	9	9
Quartz	8	11	9	16	11	15	10	13	11
Pyrite	3	6	5	4	4	11	4	8	6
Sphalerite	1	3	2	1	<1	5	2	3	2
Galena	1	2	1	2	2	2	2	2	2
Weathering minerals									
Clay minerals									
Vermiculite	3	2	3	1	2	1	2	1	2
Illite	3	2	2	1	2	<1	2	1	2
Kaolinite	7	6	7	6	5	5	7	5	6
Hydrated oxides and sulfates									
Goethite	2	2	2	2	3	2	2	2	2
Pickeringite	4	3	4	3	2	1	3	2	3
Gypsum	4	6	5	6	11	6	5	8	7
Alunogen	1	1	1	2	1	1	1	1	1
Halotrichite	4	3	4	3	4	2	3	3	3
Butlerite	3	2	2	2	2	<1	2	1	2
Coquimbite	4	5	4	7	4	7	5	5	5
Jarosite	3	4	4	3	3	3	4	3	3
Hexahydrite	2	2	2	3	2	2	2	2	2
Apjohnite	6	7	6	6	10	6	6	8	7
Römerite	2	2	2	1	1	1	2	1	2

4.3.2 Water-soluble fraction

The abundance of the soluble fraction within the tailings from the flanks of the waste deposit is low (less than 1.55 wt%) (Table 3); this may be explained by the steepness of the waste surface, which is improper to accumulation of highly soluble solid products, such as acidic and toxic metal-rich salts (hydrated sulfates). However, the soluble fraction decreases by about 60%, from the top to the bottom of the waste deposit. Consequently, during rainfalls, the tailings from the upper levels display an increased risk for environmental pollution through leaching, than the waste of the lower levels.

After an about two-year storage of sample within plastic bags, the analyses of water soluble fraction were repeated; the results are shown in Table 4 and emphasize some patterns as follow: (1) the total abundance of the soluble fraction may reach up to 3.70%, due to the precipitation of hydrated sulfates (the quaternary minerals of Jambor, 1994); (2) the larger abundances of soluble fraction are assigned to the samples collected from the upper levels, as shown by the mean that increases from the initial 0.63 wt% (Table 3) to 1.65 wt% (Table 4); (3) in terms of the water soluble fraction, the difference between the samples from the upper and the lower levels of the waste grows from 60% (Table 3) to about 80% (Table 4). Considering the close relation between the soluble fraction and the hydrated sulfates developed on the account of the primary minerals, it may be presumed that the risk of environmental pollution through leaching processes increases with time for the Dealul Negru tailings pond. Moreover, the upper levels of the waste deposit seem more favorable to the appearance of the hydrated sulfates, when specific climate conditions occur.

Data in table 4 also provide information about the relation between the tailings grain size and the abundance of the soluble fraction. Thus, it seems like the grains larger than 0.25 mm (equivalent to coarse sands) accumulate the highest amounts of soluble solids (mean of 1.44 wt%). The water soluble solids show a much lower and almost equal abundance within the fine and very fine grain-size fraction: 0.61 wt% within the fine + very fine sands, and 0.51 wt% within the silt + clay fraction. Actually, the microscopic studies performed on the tailings samples showed the preference of sulfate crystals to stick to the surface of the much larger primary mineral grains. Despite the difference of soluble fraction abundance, both the larger and smaller tailings from the lower levels of the waste deposit are depleted in soluble solids by over 80%, if compared with the waste from the upper levels (Table 4).

4.3.3 Chemical data

The chemical characteristics of the tailings from the Dealul Negru waste dam are given in table 3. In terms of composition, the tailings are similar to others reported elsewhere, in that they have high amounts of Fe, Al, S and toxic elements (e.g., Kovács et al., 2006; Kossoff et al., 2011; Stumbea, 2013). Except for Al and Mn, all elements have obviously lower amounts within the samples collected from the bottom of the tailings pond; Al and Mn display almost constant amounts within the samples from both the upper and lower levels of the waste deposit. The latter samples are intensely depleted in S, Cu, Pb, and Zn, it means that the amounts are with about 70-76% lower than the contents recorded within the samples from the upper levels; smaller decrease of abundance is also shown by Fe, Cd and Ba. Consequently, the data in table 3 suggest that the upper levels of the tailings pond are the most susceptible to environmental pollution by toxic and potentially toxic elements. Nevertheless, it is highly probable that the geochemical distribution of elements over the flanks of the waste deposit may not be exclusively influenced by the morphology of the tailings pond. Previous studies carried out on the same waste deposit show the development of thin cemented layers, on the lower, less steep levels of the waste dam. These crusts, in turn, are characterized by a depletion of most of the elements in table 3, in comparison with the elements within the main tailings (Stumbea, 2013).

4.4 Preliminary statistical analyses

The studies carried out so far on the waste deposit of Dealul Negru show that the geochemical patterns of the tailings may be influenced by at least two factors: (1) the tailings position on the vertical plane of the waste deposit (i.e., the morphology of the waste deposit); (2) the type of waste (i.e., either main tailings or crusts developed on the lower steps of the waste deposit). Consequently, Principal Component Analysis (PCA) was performed in an attempt to determine the role of each factor in the geochemical distribution of major elements and noxious elements over the surface of the tailings pond flanks.

PCA was applied to each element within two hypotheses, as follow: (1) the elemental abundance is controlled by the waste occurrence on the flank surface of the tailings pond (i.e., upper levels and lower levels); (2) the geochemical distribution of elements is controlled by the type of waste: main (regular) tailings and crusts (cemented layers). Except for S, PCA of all elements presented in table

3 helped to discriminate two clusters that group data into either main (regular) tailings or crusts, meaning that the hypothesis (2) seems to be the most credible; PCA applied to S showed no pattern when applied in either of the two hypotheses. Examples of PCA diagrams are given in figure 2.

The test of the hypothesis that the geochemical patterns are controlled by the tailings occurrence on the flank surface of the waste deposit (hypothesis 1) led to the assumption of a small or null influence.

Table 3. Geochemical properties of the waste from the tailings pond

	pH	SF	Fe	Al	S	Zn	Cu	Pb	Cd	Ba	Mn
		wt%			ppm						
Upper levels of the tailings pond (<i>n</i> = 16)											
Min.	2.28	0.04	5.16	3.92	0.16	79	47	141	0.60	517	418
Max.	3.50	1.55	12.39	10.21	4.60	609	620	893	1.90	1560	520
Mean	2.73	0.63	10.05	6.97	1.17*	161*	279	578	0.85*	969*	471
SD	0.39	0.52	2.21	1.96	1.54	161	174	280	0.40	461	35
Lower levels of the tailings pond (<i>n</i> = 19)											
Min.	2.83	0.02	3.24	4.43	0.09	45	38	40	0.20	308	327
Max.	4.66	0.43	12.08	9.33	8.99	108	934	242	1.00	1088	684
Mean	3.75	0.25	7.39	7.40	0.36*	86	73*	137	0.57	652	494
SD	0.60	0.14	2.77	1.41	2.52	17	252	51	0.24	246	105
Var. (%)**	+27	-60	-26	+6	-69	-46	-74	-76	-33	-33	+5

SF-soluble fraction (wt%); SD-standard deviation; * geometric mean; ** Variation: increase (positive values) or decrease (negative values) percentages between the means specific to samples from the top and the bottom of the tailings pond

Table 4. Water soluble fraction in the tailings (determination after two-year storage of samples within plastic bags)

	Bulk sample	Particle size		
		Coarse sand size (> 0.25 mm)	Fine and very fine sand size (0.25 – 0.063 mm)	Silt and clay size (< 0.063 mm)
Soluble fraction (wt%)				
All samples collected from the tailings pond				
	(<i>n</i> = 35)	(<i>n</i> = 10)	(<i>n</i> = 13)	(<i>n</i> = 13)
Min.	0.02	0.03	0.01	0.05
Max.	3.70	3.70	2.71	2.64
Mean	0.97*	1.44	0.61	0.51
SD	0.65	1.33	0.45	0.41
Samples from the upper levels of the tailings pond				
	(<i>n</i> = 16)	<i>n</i> = 5	<i>n</i> = 6	<i>n</i> = 6
Min.	0.34	0.78	0.34	0.61
Max.	3.70	3.70	2.71	2.64
Average	1.65*	2.47	1.24	1.54
SD	0.99	-	-	-
Samples from the lower levels of the tailings pond				
	(<i>n</i> = 19)	<i>n</i> = 5	<i>n</i> = 7	<i>n</i> = 7
Min.	0.02	0.03	0.01	0.05
Max.	1.20	1.20	0.85	0.48
Average	0.30*	0.46	0.25	0.26
SD	0.22	-	-	-
Var. (%)**	- 82	- 81	- 80	- 83

SD – standard deviation; * mean determined statistically; ** Variation: increase (positive values) or decrease (negative values) percentages between the means specific to samples from the top and the bottom of the tailings pond

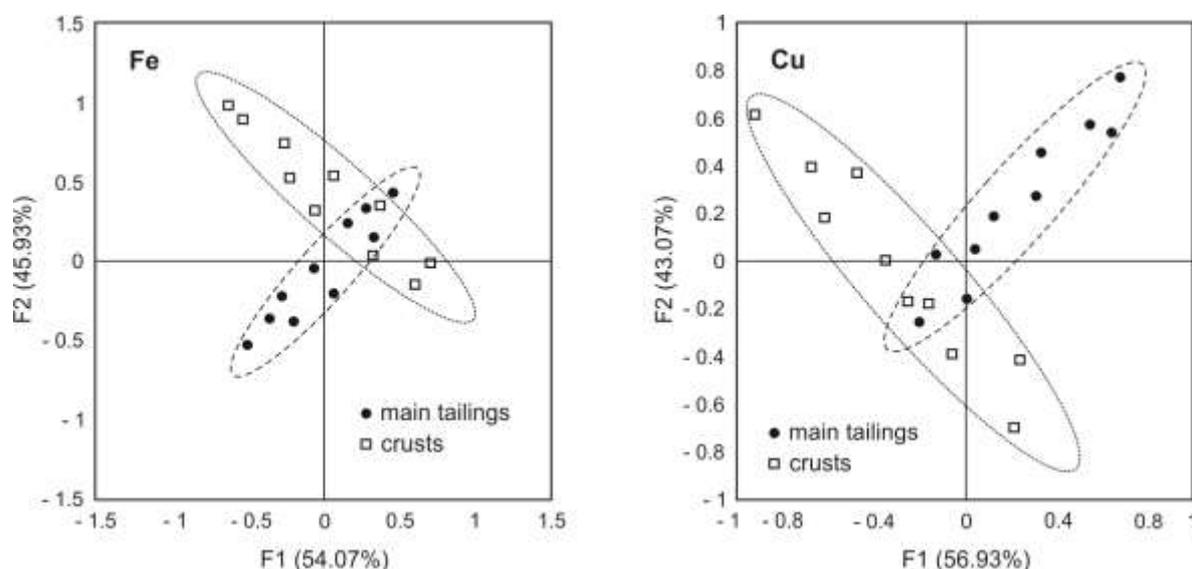


Figure 2. PCA of Fe and Cu, showing separate clusters of main tailings and crusts

It seems like, despite the clear difference of abundance identified between the tailings from the upper and the lower levels, the geochemical data belong to the same statistical population. As and Cr are the only elements that may confirm the influence of the tailings morphology on their geochemical patterns. Anyhow, further investigation, based on a large number of data and a correlation with the tailings mineralogy, must be considered in the future.

5. CONCLUSIONS

This study focused on the description of the waste from the flanks of the tailings pond of Dealul Negru, with the aim of identifying the relation between the waste deposit morphology and the pollution risk factors. The results led to the following conclusions:

(1) In comparison with the waste from the lower levels of the tailings pond, the tailings from the upper levels present a higher risk of environment pollution; the evidences consist of the lower pH, larger abundance of soluble fraction and higher amounts of both major elements and noxious elements. The risk is amplified by the climate conditions of the area: the frequently intense winds, which may remove and transport even the larger waste particles from the upper levels; the frequent rainfalls, which may remove the waste through either mechanical (water-driven removal and transport) or chemical (leaching) processes.

(2) The cemented layers developed on the lower, less steep levels of the tailings are depleted in toxic and potentially toxic metals, if compared with

the main waste. Also, they act as a protection surface against the mechanical removal of the tailings beneath. On the other hand, the crusts allow an easier circulation of particle-rich runoff and leachates from the upper levels of the tailings pond, towards the environment.

(3) Preliminary statistical analyses of the chemical data seem to point to the crusts development as the main factor responsible for the depletion of toxic metals within the tailings from the lower levels. Nevertheless, a larger number of geochemical and mineralogical data is necessary to support such a hypothesis.

(4) As a consequence of its position within the waste deposit, the tailings from the upper levels also act as a continuous, “primary” source, of acidic and toxic metal-rich waste, with a high risk of environmental pollution.

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