

Article

Mineralurgical and Environmental Characterization of the Mine Tailings of the IOCG Mine of Guelb Moghrein, Akjoujt, Mauritania

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Abstract: Since 2004, the processing of the iron oxide–copper–gold (IOCG) ore of Guelb Moghrein, Akjoujt, Mauritania, has resulted in the generation of approximately 40 million tons of mine tailings. The storage of these tailings poses significant environmental challenges particularly to surface and underground water resources. To address this issue, we propose an approach involving both mineralurgical and environmental characterization. Our mineralogical analysis reveals that the TSF tailings consist of sulfides and iron oxides associated with a silico-carbonated matrix. This mineralogical analysis also shows that the TSF tailings consist of secondary minerals, resulting from sulfides oxidation. Furthermore, our findings indicate that the chemical analysis of the TSF tailings contains potential toxic elements (PTEs) such as Cu, As, Co, Ni, Sb, and Se. Regarding the environmental characterization of the tailings, conducted through acid-based accounting (ABA) static tests, we demonstrate that leaching from the tailings generates a contaminated neutral drainage (CND).

Keywords: IOGC ore; mine tailings; mineralurgical characterization; static prediction test; CND; PTE; Guelb Moghrein; Akjoujt; Mauritania



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1. Introduction

Since 2004, the Mauritanian Copper Mines (MCM), a multinational based in Canada, has an open pit of the sulfide portion located in the iron oxide–copper–gold (IOCG) deep domain of the Guelb Moghrein mine, Akjoujt, Mauritania [1–6]. The IOCG deposit has total remaining measured and inferred resources of 23.7 million tons (Mt) at 1.88% Cu and 1.41 g/t Au. The commercial production in an open pit operation commenced in October 2006 with a projected annual production of 30,000 t of copper and 70,000 ounces of gold [2]. The mineralization is embedded in the siderite of an archean metacarbonate (FMC) body deformed into a breccia and then permeated by hydrothermal circulations, thus allowing the ore deposition by the replacement of diagenetic dolomitic limestones [3,7]. The mining activities at the Guelb Moghrein constantly generate large amounts of processing wastes (flotation and magnetic separation). A total of 40,000,000 Mt of tailings were stored

inside the mining site in Tailings Storage Facilities (TSFs). This site is composed of three tailings ponds: TSF1 (5,055,259 Mt), TSF2 (23,694,803 Mt) and TSF3 (10,409,000 Mt). These tailings are hazardous with respect to the surrounding ecosystems and have negative socioeconomic repercussions on the communities. Like many other geochemical and geotechnical stability issues, the study of the environmental behavior of these mine tailings requires a good understanding of the various factors involved at the scale of the TSF ponds. Several transformations of the TSF mine tailings in their current state have been observed as a response to climate and site conditions that greatly affect the TSF, notably the geochemical processes which involve factors such as reduction–oxidation, dissolution, precipitation and adsorption–desorption [8–11]. Reactive sulfide and arsenide minerals, such as pyrite (FeS_2), pyrrhotite ($(\text{Fe}_{1-x}\text{S})$), arsenopyrite (FeAsS), chalcopyrite (CuFeS_2), cubanite (CuFe_2S_3), clinosafflorite ($(\text{Co,Fe,Ni})\text{As}_2$) and gersdorffite (NiAsS) in contact with water and air oxidize, leading to acid mine drainage (AMD) formation, and hence an increase in the solubility of various potentially toxic elements (PTEs) [11–17]. This phenomenon leads to the transfer of metallic trace elements (MTEs) to the soils and water resources (both surface and underground) which is harmful to biodiversity and health [18,19]. However, the dissolution of carbonates and silicate minerals present in the mine tailings can neutralize the acidity produced [9,12,20,21] and limit the impact of this phenomenon at the stage of contaminated neutral drainage (CND) [8,22–24]. The formation of secondary minerals such as oxyhydroxides, hydroxysulfates, arsenates, sulfates and halides resulting from the neutralization of AMD can generate hardpan, which consists of dense and hard crusts in semi-arid climatic conditions [25]. The hardpan prevents water penetration and oxygen diffusion due to pore clogging; and consequently, it decreases porosity and permeability. Secondary minerals can also be considered as metal scavengers because of the significant retention capacity of metals by adsorbent minerals, which reduces the mobility of metals in the pore water and leads to their release into the surrounding environment [20,26–39]. Moreover, the arid and hot climatic context of the Akjoujt region is characterized by high evaporation rates (>3500 mm/year) in addition to the increasing rainfall deficit (<70 mm/year) and a poor vegetation cover. Therefore, these climatic conditions underscore the precipitation of salt crusts on the surface, which once subjected to wind erosion can contaminate the surrounding ecosystems (water, air, soil) [40]. In addition to the complexity of these phenomena, we must refer to other geotechnical features such as the formation of cracks, matric suction, salt precipitation, crack clogging, crust consolidation and volumetric shrinkage, which may affect the stability of the TSF mine tailings.

The overall objective of this study is to conduct, for the first time in Mauritania, a detailed mineralurgical and environmental characterization on the three TSF mine tailings in order to show the problems that the IOGC mining activities could generate on the environment under the arid climate conditions of Akjoujt. This must be completed before the end of mining operations in order to prevent high rehabilitation costs. Furthermore, this study is the first to demonstrate that the minerals, in this site, resulting from sulfides oxidation such as oxyhydroxides, arsenates, sulfates, and oxyhalides are mainly present in the salt precipitates (TSF2S and TSF3S), and this ultimately contaminates the environment through toxic elements such as Cu, As, Co, Ni and Se. Moreover, we conducted acid-based accounting (ABA) static tests on the TSF tailings, and our results show that waste leaching generates a contaminated neutral drainage (CND), which carries potential toxic elements (PTEs)—hence the need to develop mitigation approaches through valorization mechanisms.

2. Materials and Methods

2.1. Presentation of the Study Area

The Guelb Moghrein Cu-Au mine lies 4 km to the northwest of Akjoujt City, capital of the Wilaya of Inchiri (western–central region of Mauritania), and 250 km to the northeast of Nouakchott ($19^\circ 45'$ Latitude North and $14^\circ 25'$ Longitude West, Figure 1). The Akjoujt region is located on the southwestern outskirts of the Sahara Desert where the climate is

of hot and arid-desert type with maximum and minimum temperatures of 47 and 12 °C, respectively. The maximum wind speed is about 14 m/s, and wind blows in a southwesterly direction mainly. The hygrometric degree is generally low, but its variations from one season to another are great. In summer, humidity can reach 75%. Atmospheric precipitation is almost insignificant, and it generally rains in August where the annual average is less than 70 mm. The evaporation rate far exceeds the rainfall all year long, where it could be as high as 3500 mm/year, i.e., 50 times the rainfall rate. The Bennichab water table, located at about 113 km, at a straight line from Akjoujt city and 230 km from Nouakchott, ensures the supply of fresh water to the population of Akjoujt while salt water is used at the ore-processing plant.

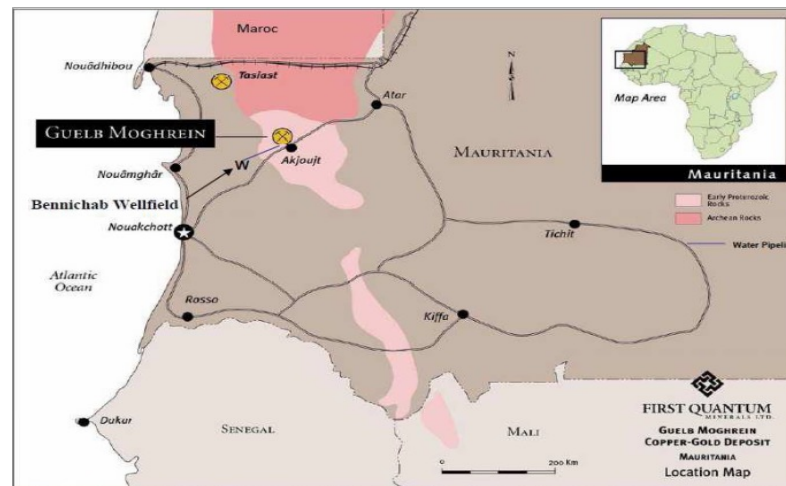


Figure 1. Geographic location of the Guelb Moghrein area.

2.2. Geological Context of the Deposit and Mineralization

The Guelb Moghrein IOCG mineralization, located in the West African Craton, shares several similar characteristics with other deposits around the world such as the IOCG deposits in northeastern Australia, namely the Osborne, Starra and Ernest Henry deposits, and the Salobo deposit in Brazil [1–7,41–45]. The lithostratigraphy of the supracrustal rocks in the Akjoujt area belongs to the Mauritanide greenstone series, which consists of two lithological sequences of Archean age, and is separated by an angular unconformity. The lower sequence known as the Eizzene group follows the basement rocks and is unconformably overlain by the Oumachoueima group. Detailed open pit mapping in Figure 2 shows that the main lithologies at Guelb Moghrein are metasedimentary and metavolcanic rocks of the Sainte Barbe volcanic unit and metabasalts of the Akjoujt unit. A metacarbonate (FMC) body that contains the IOGC orebody is associated with the Akjoujt meta-basalt unit. In contact with wall-rock amphibolites, the FMC body is enveloped by an alteration halo up to 40 m wide, corresponding to an extent of Fe-Mg clino-amphibole alteration and consisting of biotite, actinolite, grunerite, chlorite, calcite, albite, and quartz [3,7]. From a structural point of view, the Akjoujt area is made up of a complex set of folded and stacked thrust sheets. Five deformation events (D1 to D5) and related metamorphic overprints are distinguished [3,46,47]. The D1 deformation mainly affects the Eizzene group, resulting in open folds and a weak regional foliation S1. A peak metamorphic, amphibolite-facies hornblende–plagioclase paragenesis is developed parallel to the S1 foliation in the Akjoujt metabasalts. Hornblende–plagioclase thermometry indicates 580 ± 40 °C for this metamorphic stage [3]. During the D2, thrusting of the Sainte Barbe volcanic unit to the NNW created a layer-parallel S2 foliation, which formed a crenulation cleavage with the S1 foliation and recumbent folds. A peak metamorphic, upper greenschist facies of garnet–biotite paragenesis is formed parallel to the S2 foliation in the Sainte Barbe volcanics. Garnet–biotite geothermobarometry records a metamorphic P-T peak of about 410 ± 30 °C and 2

to 3 Kbar for this metamorphic stage [3]. The rocks of the Akjoujt metabasalt unit were retrogressed, and a biotite–actinolite paragenesis is formed parallel to the S2 foliation. This D2 deformation event is contemporaneous with the hydrothermal mineralization and dates back to 2492 ± 9 Ma. The main IOCG mineralization stage featured syn-D2 thrusting along NE-vergent thrust zones in the FMC body [4]. The Brecciation of siderite (FMC) during D2 was followed by a strong metasomatic overprinting with the hydrothermal transport of Fe, Mg, K, Rb, Sr, Ba, Ni, Co, Cu, Bi, Mo, As, Au and REE in the host rocks and the formation of the gold-bearing hydrothermal assemblage [2]. During the D3 deformation event, almost orthogonal fabrics were created in all units. D3 shear zones are characterized by a closely spaced S3 foliation. Coupled with hydrothermal fluid flow, this third deformation event occurred at 1742 ± 12 Ma in the lower greenschist facies formations. It may also have been responsible for the truncation of the mineralized horizons of the Guelb Moghrein deposit [4,48]. Gentle to moderate folds with ENE–WSW trending fold axes deformed the thrust sheets during D4 and D5, which are correlated with thrusting along the sole thrust during the Westphalian [3,46,47]. D4 created a conjugate set of S4 foliations within the Guelb Moghrein deposit, and D5 is characterized by a set of NNE–SSW trending faults with minor offsets [3]. The FMC body of the Akjoujt metabasalt unit is composed mainly of a brecciated siderite hosting the hydrothermal IOCG mineralization, which is closely associated with the Banded Iron Formation (BIF) and is restricted to a 30 m wide tabular breccia zone developed parallel to discrete shear zones [3]. The primary mineralogy in the breccia zones is dominated by pyrrhotite and chalcopyrite, and it is accompanied by Fe–Co–Ni arsenides, arsenopyrite, cobaltite, uraninite, Bi–Au–Ag–Te minerals, magnetite, Fe–Mg clinoamphiboles, chlorite, graphite, apatite, xenotime and monazite [3,7,46,48–51]. Gold is found either original form, in solid solution with silver (electrum) or bismuth (maldonite) or in a Bi–Au–Ag–Te complex and associated with arsenopyrite (FeAsS) and clinosafflorite $[(\text{Co,Fe,Ni})\text{As}_2]$. The paragenetic assemblages indicate a relatively high formation temperature of 400–450 °C consistent with retrograde metamorphic conditions. Structural control of this mineralization is provided by the D2 of the shear zones [3,47,48]. Ex-solution mineralogy includes troilite (FeS), pentlandite $((\text{Fe,Ni})_9\text{S}_8)$, cubanite $(\text{CuFe}_2\text{S}_3)$, mackinawite $((\text{Fe,Ni})_{1+x}\text{S})$ and nickeline (NiAs). This assemblage was formed within a temperature range of 200–250 °C [48] during the D3 deformation of the retrograde metamorphism with lower green schist facies [3,47].

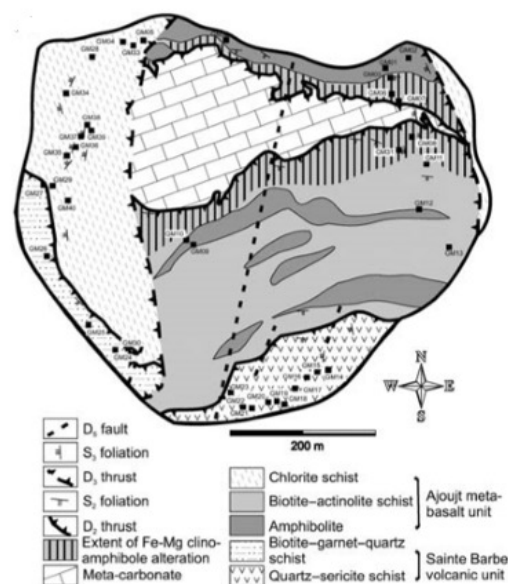


Figure 2. Schematic geological map of the Guelb Moghrein open pit showing the major structural features and the alteration halo surrounding the metal carbonate (FMC) formation, which hosts the IOCG mineralization (modified after [3]). The almost orthogonal fabrics of the D2 and D3 deformation stages should be noted.

2.3. Tailings Storage Facilities (TSF)

The ore minerals are released by crushing, grinding and then separating the valuable component from the gangue following a series of processes such as flotation (recovery of Cu-Au) and magnetic separation (recovery of Fe_3O_4). The tailings obtained after thickening are stored in the TSFs which consist of vast depressions circumscribed on natural substratum, which are essentially formed by quartzites, altered schists and metabasalts associated with banks of Banded Iron Formation (BIF) remobilized and leveled by machinery. The TSF consists of a large pond divided into three parts (Figure 3): Guelb Moghrein has an old storage facility (TSF1) commissioned in 2007 and two active tailings storage facilities, TSF2 and TSF3 commissioned in September 2009 and February 2015, respectively. The oldest ponds with a storage capacity of 53 ha (TSF1) and 162 ha (TSF2) resulting from the flotation process contain magnetite and will be reclaimed and processed at the end of the mine lifespan to recover the contained gold, copper and magnetite. The magnetite processing plant operating by wet low-intensity magnetic separators (WLIMSs) consists of extracting the magnetite (Fe_3O_4) from copper ore flotation tailings as a concentrate grading of about 96% Fe_3O_4 , e.g., 65% Fe. The nonmagnetic tailings of the circuit go to the final tailings thickener before they are stored in the TSF3 pond laid over premises covering an area of 163 ha.



Figure 3. Satellite view (Google Earth) showing the three TSF ponds and the open pit of the Cu-Au mine of Guelb Moghrein.

2.4. Sampling

Process (flotation, magnetic separation) tailings are stored in three TSFs, which are 4 m (TSF1), 8 m (TSF2) and 4 m (TSF3) high, respectively. The sampling consisted of collecting process tailings and salt precipitates from all TSFs. A total of 26 samples of process tailings were selected from the three TSF basins: 7 from TSF1, 4 from TSF2 and 15 from TSF3 (Figure 4). Two samples of salt precipitates were taken at the top surface (0–5 cm) of TSF2 and TSF3 (TSF2S and TSF3S, respectively). All sampling points were geo-referenced by Global Positioning System (GPS coordinates are given in Appendix A), according to a planned map and to accessibility to the site. Tailings samples were taken with a small caterpillar excavator at the top of TSF1 (0–4 m depth) and TSF2 (0–5 m depth) and by dredging the top of TSF3 (0–1.5 m depth) (Figure 5). The TSF1 and TSF2 materials consist of alternating unoxidized (gray, black colors) to oxidized (brownish, red, orange colours) material of a few centimeter thick layers; whereas the TSF3 materials are more or less homogeneous mixtures of oxidized and non-oxidized tailings. Five kilograms of materials were collected at each sampling point. Each sample was put in a polyethylene bag with a shovel and referenced. In the laboratory, the samples were successively mixed, homogenized, quartered, and divided by rotary dividers in order

to constitute representative composite samples of about 1 kg for each TSF, in view of physicochemical, mineralogical and environmental characterization.

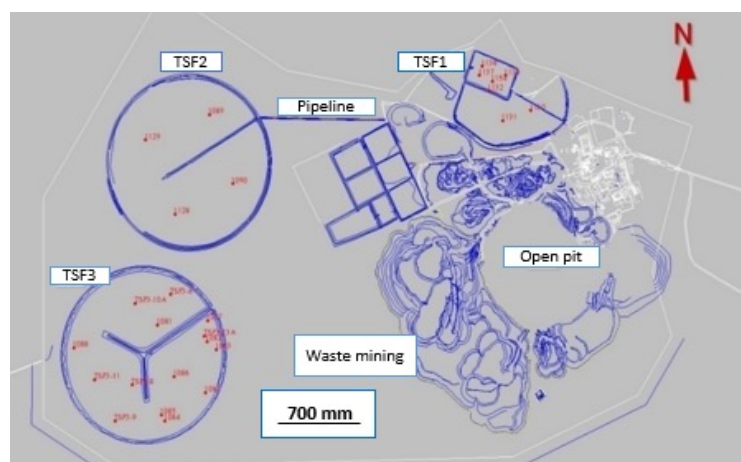


Figure 4. Location of the sampling points in the three TSF ponds.

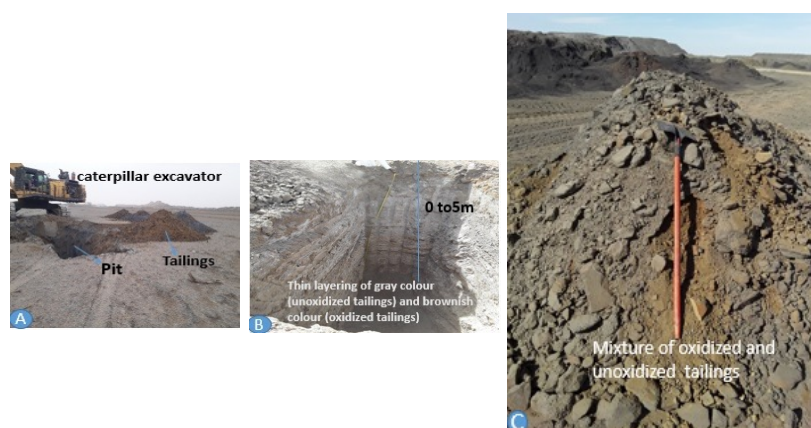


Figure 5. Sampling procedure of TSF1 (A), TSF2 (B) and TSF3 (C) tailings.

2.5. Methods

Several methods were carried out to determine the physical, chemical and mineralogical characteristics of the TSF tailings. The particle size was determined by using a laser analyzer in the laboratories of the Institut National de Recherche et d'Analyse Physico-Chimique (INRAP). The Atterberg limit of the TSF tailings was performed to determine the liquidity limit (wL) by cone penetrometer and the plasticity limit (wP) by rollers according to NF P94-052-1 and NF P94-051, respectively. These parameters were measured in the Office National des Mines (ONM). The mineralogical analysis was performed by using X-ray diffraction (XRD); about 10 g split aliquot of sample was pulverized, and the resultant power was analyzed by a means system in order to identify the major minerals present in each sample. The mineralogical analysis was performed by using X-ray diffraction (XRD); about a 10 g split aliquot of sample was pulverized, and the resultant power was analyzed in order to identify the major minerals present in each sample. XRD data collection was completed by using a Bruker D8 ADVANCE diffractometer (Bruker AXS Inc., Fitchburg, WI, USA) with CuK α radiation operating at 40 kV, 40 mA, and 0.025 per second step size. The samples were scanned over a 2–65° 2 θ angular range at a step size of 0.025° 2 θ per 3 s. Data interpretation was completed by using X' Pert High Score Plus (<https://www.pharmaceuticalonline.com/doc/xpert-highscore-plus-mdash-x-ray-powder-patte-0001>, accessed on 14 November 2023) which

allows identifying and indexing the minerals; PDF2 was also used for database and data interpretation. For metallographic observation, decarbonation tests were carried out on the granulometric fractions (150–300 μm) of the TSF1 and TSF2 tailings and over 75 μm for TSF3 tailings. The protocol consists of putting a sample of 20 g in the 100 mL beaker and adding 40 mL of hot HCL diluted to 10%. The suspension with a liquid/solid ratio (L/S) of 2:1 is placed on a hot plate at 50 °C for 2 min to avoid the dissolution of oxides (magnetite) and silicates. At the end of the test, the residue was washed with distilled water in order to eliminate the fine fraction in suspension. Polished sections were prepared with the dense fractions for observation by optical microscopy. The concentrations of the major elements—namely, Si, Ca, Mg, Al, Fe, Na and K and Au metal—were analyzed by atomic absorption spectroscopy (AAS, Varian Pala, USA). In addition, the minor elements (such as As, Cu, Co, Ni, Pb, Sb, Se, Cd, Cr, Mn, Ti, P, Zn, B, Be, Li, Mo, Ba Sr, Th, V and Zr) were determined by inductively coupled plasma—atomic emission spectroscopy (ICP-AES-Perkin Elmer Optima 3000 spectrometer-detection limit < 5 mg/kg). TSF samples were finely grounded in an agate mortar and dissolved in a total tri-acid (HClO_4 , HF and HNO_3) on a hot plate at 95 °C until complete dryness. The complete dissolution of the residue was achieved by using 5 mL of concentrated HCL. Both AAS and ICP-AES methods were applied in the Office National des Mines (ONM). The S was analysed by X-ray fluorescence (XRF) at the metallurgy laboratory of the MCM. Equivalent calcium carbonate content (% CaCO_3) was determined by the volumetric method by using a Bernard calcimeter (POBEL, Madrid, Spain).

The static tests were carried out at the National Institute of Research and Physico-chemical Analysis to measure the acidic and neutralization potentials of the TSF tailings. The pH paste test consists of mixing samples of 20 g (particle size < 250 μm) with 10 mL of deionized water in a 50 mL polyethylene tube with a solid/liquid ratio (S/L) of 2:1, and then the suspension was agitated mechanically (20 rpm) for 24 h to make a paste. The paste pH was then measured by inserting a pH electrode into the paste. The pH value of the paste allows appreciating the degree of advancement of the acid generation process of the studied tailings [52]. The acid–base accounting (ABA) static test was used for the neutralization potential (NP) determination by using the method of [53]. The authors propose the modification of the Sobek test, eliminating the heating step (at 90 °C), as did [54], and we propose a longer time for the test (between 48 h and one week) while taking into account the more or less slow dissolution kinetics of certain carbonates. Indeed, calcite is more reactive than dolomite which is, in turn, more reactive than ankerite and siderite [26,55]. In this study, the protocol consisted of taking 2 g of sample in a polyethylene tube and adding 25 mL of 0.1 N HCL (according to the Fizz test). The suspension was carried under mechanical agitation for 24 h and 48 h in order to evaluate the equilibrium between the acid-generating potential (AP) and the neutralizing potential (NP) of TSF mine tailings. Then, 10 mL of the filtered solution was taken, and the residual acid is titrated by 0.1 N NaOH up to pH = 7. The neutralization potential (NP), expressed in kg CaCO_3/t , is determined according to the following formula: $NP = 50[x - y(b/a)]/c$ where NP is the kg CaCO_3/t , 50 is a conversion factor, a is the HCL normality (mol/L), b is the NaOH normality (mol/L), x is the HCL volume (mL), y is the NaOH volume (mL), and c is the sample mass (g). The acid potential (AP), also expressed in kg CaCO_3/t , can be calculated by using the total sulfur in the sample (determined by chemical analysis) and multiplying it by a stoichiometric coefficient of 31.25 as proposed by [56]: $AP = 31.25 \cdot \% S_{total}$. The net neutralization potential (NNP = NP–AP) was calculated. Materials are considered non-acid generating when NNP is positive. There is a zone, called the uncertainty zone, where the nature of the material is difficult to define given its acid-generating potential. For NNP, the uncertainty zone is generally between -20 and $+20$ kg CaCO_3/t [57]. However, a discharge with $NNP > 20$ kg CaCO_3/t is considered as non-acid generating, whereas $NNP < -20$ kg CaCO_3/t is considered as acid-generating. Typically, the material is considered non-acid generating ($NP/AP > 3$), uncertain ($1 > NP/AP > 3$), and acid-generating ($NP/AP < 1$) [58]. The criteria for interpreting the statistical tests of PNN and PN/PA ratio

can be combined together in a graphical representation to define the zone of acid generation and consumption as well as the degree of uncertainty (adapted from [59]).

3. Results and Discussion

3.1. Site Prospection

Processed tailings of the Cu-Au Mine of Guelb Moghrein Akjoujt are conveyed through a pipeline as a pulp (70% solid content) to the retention ponds (Figure 6). The tailings are discharged by alternating between spigots and by a controlled rotating aerial method that ensures sequential drying of the tailings. This method prevents the stacking of the tailings and the settling of water in the ponds. The ponds are surrounded by protective dykes. Water is drained toward a pumping system, laid down at the center of the TSF, to be reused as water at more than 20% in the flotation circuit.



Figure 6. Mode of tailings disposal in the TSF3 (A–C).

Advanced oxidation has been observed through the TSF1, TSF2 and TSF3 tailings of Guelb Moghrein; as the tailings progressively desaturate, in a relatively dry pond, the oxidation of the tailings becomes more significant. However, progressive dewatering results in the formation of highly oxidized tailings and highly hardened crusts. Figure 7 shows that the depths of tailings oxidation vary within the same pond and from one site to another. Sulfide tailings produced by the mineralogical treatment of base and precious metals have several characteristics similar to the reactions that take place in the tailings storage facilities under climatic conditions. In reactive mine tailings, iron sulfides, the most common of which are pyrite (FeS_2) and pyrrhotite (Fe_{1-x}S), oxidize, and they produce acidity in contact with water and air [11,13]. The neutralization of acidity by the dissolution of alkaline minerals generally produces secondary mineral phases [9,20,21]. A characteristic associated with the neutralization process observed across tailings facilities is the precipitation of secondary minerals [20], forming hard pans, which are physically dense and mechanically hard crusts under semi-arid climatic conditions [25]. These hardpans, typical of sulfide mine tailings, have long been the subject of several research works dealing with their geochemical behavior. The oxidation product of these layers are composed mainly of oxyhydroxides, hydroxysulfates, arsenates, sulfates and halides. These secondary minerals significantly affect the geochemical properties of the tailings behavior because they can retain dissolved metals by co-precipitation or adsorption. They also form a resistant barrier to prevent water infiltration and oxygen diffusion, which are the two main concomitant agents of acid mine drainage [20,26–37,39,60].

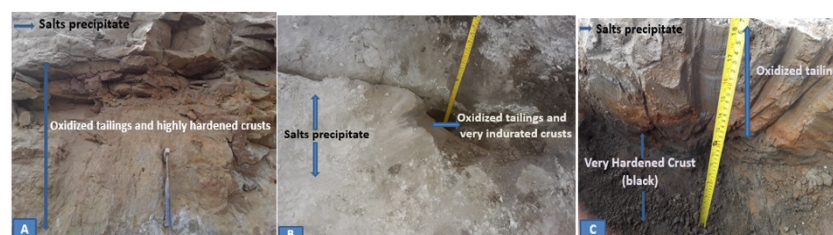


Figure 7. Oxidation of tailings and formation of highly indurated crusts. (A) TSF1 (317 cm); (B) TSF2 (38 cm) and (C) TSF3 (53 cm).

Numerous phenomena have been observed in the TSF tailings of the Guelb Moghrein mine regarding the hydrogeotechnical behavior associated with the arid climate. Particle size and mineralogical characteristics promote the rapid formation of cracks (Figure 8A) in the tailings initially saturated with water under the effect of self-weight. Thus, as the tailings become desaturated, numerous cracks would form on the surface of the TSF tailings at the Cu-Au mine of Guelb Moghrein, which is similar to other gold mines around the world such as the Bulyanhulu in Tanzania [61,62] and the Manitou tailings in Canada. Excessive evaporation leads to the removal of the hydraulic barrier and induces oxygen diffusion, which consequently causes the likely production of AMD [47,63,64]. However, in more arid countries, such as Akjoujt in Mauritania, Western Australia and Bulyanhulu in Tanzania, the precipitation of salts (Figure 8B) on the surface during evaporation results in the development of thin and thick salt crusts, which can significantly reduce the rate of evaporation. Therefore, this phenomenon could impede excessive desaturation and minimize the entry of oxygen and therefore prevents the production of AMD [62,65]. The fine efflorescents (salt precipitates) and the abundance of fine particles size in the TSF tailings may contaminate the surface and underground water resources, air and soil and jeopardize public health due to their MTE and asbestiform amphiboles content (actinolite, cummingtonite, grunerite, anthophyllite). In addition, the progressive drying of the tailings leads to consolidation and gain in mechanical strength [66,67], like the examples of the Guelb Moghrein. The same phenomenon has been observed at the Bulyanhulu mine. In addition to this, drying scales are observed at the surface of the TSF1, TSF2 and TSF3 tailings (Figure 8C). In addition, wide and deep cracks (Figure 8F) result from the deposition of thick layers of fresh tailings in the cracks of old layers, which could lead to the clogging of cracks (Figure 8D) during dewatering [61] and the subsequent formation of highly indurated crusts (Figure 8E). Cracking also accelerates evaporation, which not only occurs on the surface of the deposits but also on the surfaces caused by cracking [68–70]. Thus, the penetration of water and air at a certain depth enables the triggering of AMD [15,71]. Here, it should be noted that cracking and salinity are two important factors that can enhance evaporation through the tailings piles [68,72].

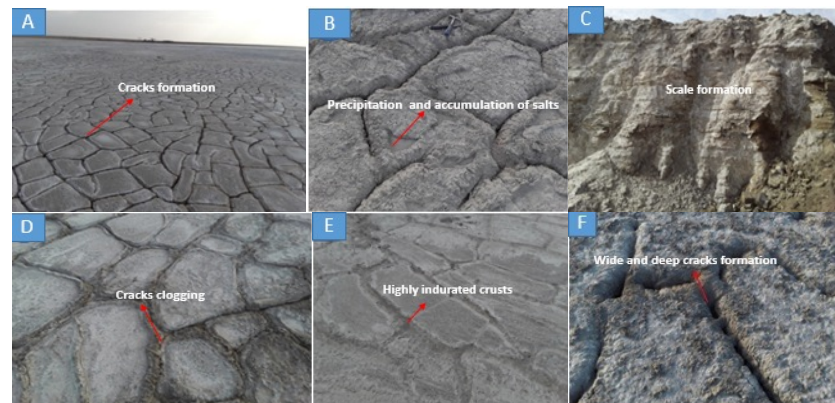


Figure 8. Hydro-geotechnical behavior of the TSF mine tailings (A): Cracks formation at the disposal tailings ponds (TSF3); (B): significant precipitation and accumulation of salts on the surface (TSF2); (C): formation of drying scales on the surface of mine tailings (TSF1); (D): clogging of cracks (TSF2); (E): formation of highly indurated crusts (TSF3); (F): formation of wide and deep cracks (TSF2).

3.2. Physical Properties of the TSF Tailings

The results of particle size distribution are displayed in the curve semi-logarithmic mark of the cumulative percentage of passing grains as a function of particle size (Figure 9).

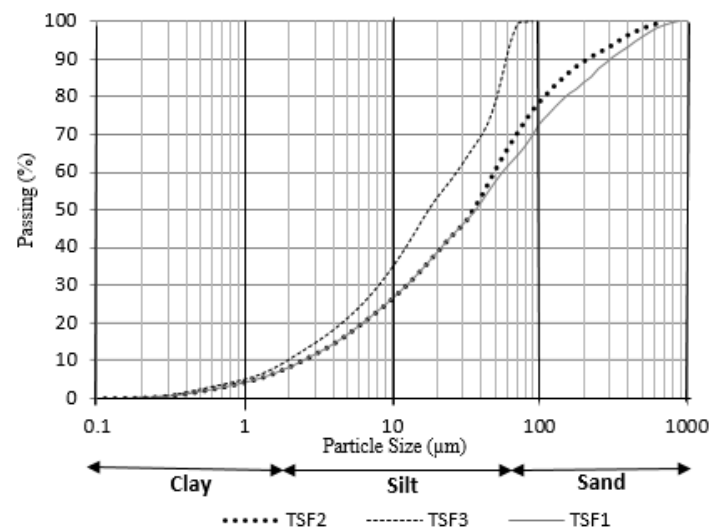


Figure 9. Particle size distribution of the TSF tailings.

Particle size and geotechnical parameters of the TSF tailings are given in Table 1. From the distribution curve, the main characteristics of the particle size parameters of the TSF, expressed as D10, D30, D50, D60, and D90, can be determined. They represent, respectively, the diameter of the grains for 10, 30, 50, 60 and 90% of the sieve (μm). D50 represents the average diameter of the grains, while that of the D90 represents the diameter of most of the grains constituting the TSF tailings. The coefficient of uniformity ($C_u = D_{60}/D_{10}$) and coefficient of curvature ($C_c = (D_{30})^2/(D_{10} \times D_{60})$) are quantitative indexes used to describe particle gradation. Considering the TSF1, TSF2 and TSF3 tailings, the coefficient of uniformity is 22.79, 20.02, and 14.19, respectively, and the coefficient of curvature corresponds to 1.24, 1.29, and 1.14, respectively. Based on these results, the C_u values are higher than 5 and the C_c values are between 1 and 3; all TSF tailings are classified as well-graded soils [73–77]. In terms of particle size distribution, all TSF tailings are of heterogeneous granulometry that consists of silt > sand > clay for the TSF1 and TSF2 tailings and silt > clay > sand for the TSF3 tailings. These results confirm that TSF3 tailings are finer with a P 80 of 100% (P 80 is the percentage of particles passing through an 80 microns sieve) compared to TSF1 and TSF2 tailings whose particle sizes show a P 80 of 66.67% and 73.39%, respectively. The use of the Soil Textural Triangle developed by the U.S. Department of Agriculture [78] according to the proportion of the granulometric fractions allows classifying the TSF3 tailings as silt, while the TSF1 and TSF2 tailings are classified as silty loam (Figure 10). The specific surface area (SSA) of all TSF tailings was $3 \text{ m}^2/\text{g}$, which is attributed to their low clay minerals content.

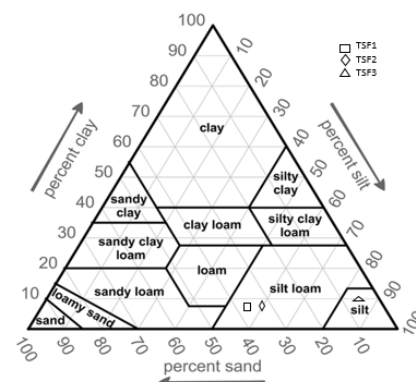


Figure 10. Positioning of the TSF tailings on the Soil Texture Triangle (USDA, 2017) [78].

During the Atterberg limit tests, the liquidity limit of the TSF tailings could not be determined by the Casagrande cup due to their low clay content, but this test was performed using the cone penetrometer. The results of the Atterberg limit show that the plasticity index values ($\%PI = wL (\%) - wP (\%)$) of the TSF1, TSF2 and TSF3 tailings are 5.11, 5.33, and 7.08% respectively. Some authors [12,17] have argued that tailings from hard rock mining generally display low plasticity index values ($PI < 10\%$). Here, [15] reports that the liquidity limit amounts to $wL < 40\%$ and the plasticity limit amounts to $wP < 15\%$. These TSF tailings can be considered as very low (TSF1) to low in plasticity (TSF2 and TSF3) and showed silt-sized characteristics, which is in accordance with the data reported in the literature [15,70,79].

Table 1. Particle size and geotechnical parameters of the TSF tailings.

Parameters	TSF1	TSF2	TSF3
D90 (μm)	306.24	213.57	59.49
D60 (μm)	56.15	49.22	27.31
D50 (μm)	36.91	35.31	17.59
D30 (μm)	12.54	12.52	8.08
D10 (μm)	2.46	2.45	1.92
Coefficient of uniformity	22.79	20.02	14.19
Coefficient of curvature	1.24	1.29	1.14
Passing 80 μm (%)	66.76	73.49	100
Sand sized > 63 μm	37.71	32.24	5.72
Silt sized 2–63 μm	54.82	59.92	85.05
Clay sized < 2 μm	7.47	7.47	9.23
Specific surface area (m^2/g)	3	3	3
Liquid limit wL (%)	20.10	18.09	20.59
Plastic limit wP (%)	14.99	12.76	13.51
Plasticity index PI (%)	5.11	5.33	7.08

3.3. Mineralogical Analysis

The mineralogical analysis of the TSF tailings and salt precipitates was performed by using X-ray diffraction and the metallographic observation of polished sections. The results of XRD showed (Figure 11) that these samples consist mainly of iron oxides (magnetite: Fe_3O_4), sulfides (stibnite: Sb_2S_3 , anilite: Cu_7S_4 , bismuthinite: Bi_2S_3 , stembergite: AgFe_2S_3 , paraganajautite: $\text{Bi}_2(\text{Se},\text{S})_3$), arsenide (löllingite: FeAs_2 , skutterudite: $(\text{Co},\text{Ni},\text{Fe})\text{As}_3$, clinosafflorite: $(\text{Co},\text{Ni},\text{Fe})\text{As}_2$), koutekite: (Cu_5As_2) and copper sulfosalts (tennantite: $(\text{Cu},\text{Fe})_{12}\text{As}_4\text{S}_{13}$) associated with gold tellurides (sylvanite: $(\text{Au},\text{Ag})\text{Te}_2$, krennerite: Au_3AgTe_2). The carbonates are composed of siderite: $(\text{Fe},\text{Mg})\text{CO}_3$, dolomite: $\text{CaMg}(\text{CO}_3)_2$, ankerite: $\text{Ca}(\text{Fe},\text{Mg},\text{Mn})(\text{CO}_3)_2$, calcite: CaCO_3 , and sphaerocobaltite: CoCO_3 . Thus, some silicates are identified such as phyllosilicates

(clinochlore: $(\text{Mg},\text{Fe}^{2+})_5\text{Al}(\text{OH})_8/\text{AlSi}_3\text{O}_{10}$, nimite: $(\text{Ni},\text{Mg},\text{Al})_6(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_8$, pyrophyllite: $\text{Al}_2(\text{Si}_4\text{O}_{10})(\text{OH})_2$, halloysite-7Å: $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$, corrensite: $(\text{Mg},\text{Fe})_9((\text{Si},\text{Al})_8\text{O}_{20})$

$(\text{OH})_{10}\cdot n\text{H}_2\text{O}$, biotite: $\text{K}(\text{Mg},\text{Fe})_3\text{AlSi}_3\text{O}_{10}(\text{F},\text{OH})_2$, brindleyite: $((\text{Ni},\text{Al})_3(\text{Si},\text{Al})_2\text{O}_5(\text{OH})_4)$, muscovite: $((\text{KF})_2(\text{Al}_2\text{O}_3)(\text{SiO}_2)_6)$, inosilicates (plancheite: $\text{Cu}_8\text{Si}_8\text{O}_{22}(\text{OH})_4\cdot\text{H}_2\text{O}$, omphacite: $((\text{Ca},\text{Na})(\text{Mg},\text{Fe},\text{Al})\text{Si}_2\text{O}_6)$), amphiboles asbestiform

(actinolite: $\text{Ca}_2(\text{Mg},\text{Fe})_5(\text{OH},\text{F})_2(\text{Si}_4\text{O}_{11})_2$, cummingtonite: $((\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$, anthophyllite: $(\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$), amphiboles sodic

(ferroglaucophane: $(\text{Na}_2\text{Mg}_3\text{Al}_2(\text{Si}_8\text{O}_{22})(\text{OH})_2)$), zeolite (faujasite $(\text{Na}_2,\text{Ca},\text{Mg})_{3.5}(\text{Al}_7\text{Si}_{17}\text{O}_{48})\cdot 32\text{H}_2\text{O}$, stilbite-Ca: $\text{NaCa}_4(\text{Si}_{27}\text{Al}_9)\text{O}_{72}\cdot 28\text{H}_2\text{O}$) and quartz: SiO_2 .

A wide range of secondary minerals are identified in the salt precipitates that are associated with all TSF tailings, such as oxyhydroxides claudetite: As_2O_3 , pyrochroite: $\text{Mn}^{2+}(\text{OH})_2$, hydrotalcite: $(\text{Mg}_6\text{Al}_2(\text{OH})_{16}\text{CO}_3\cdot 4\text{H}_2\text{O})$, sulfates (plumbojarosite: $\text{Pb}_{0.5}\text{Fe}^{3+}_3(\text{SO}_4)_2(\text{OH})_6$, devilline: $\text{CaCu}_4(\text{SO}_4)_2(\text{OH})_6\cdot 3\text{H}_2\text{O}$, serpierite: $\text{Ca}(\text{Cu},\text{Zn})_4(\text{SO}_4)_2(\text{OH})_6\cdot 3\text{H}_2\text{O}$, ramsbeckite: $\text{Cu}_{15}(\text{SO}_4)_4(\text{OH})$, starkeyite: $\text{MgSO}_4\cdot 4\text{H}_2\text{O}$, kieserite: $\text{MgSO}_4\cdot \text{H}_2\text{O}$, cobaltkieserite: $\text{CoSO}_4\cdot \text{H}_2\text{O}$, aplowite: $\text{CoSO}_4\cdot 4\text{H}_2\text{O}$, hexahydrite: $\text{MgSO}_4\cdot 6\text{H}_2\text{O}$, gypsum: $\text{CaSO}_4\cdot 2\text{H}_2\text{O}$,

ascending order of resistance to alteration in oxidized tailings. These iron sulfide minerals were not found by XRD conducted on bulk-tailing samples. Iron oxides (magnetite and hematite), oxyhydroxides and chalcopyrite are omnipresent in all polished sections. The grain sizes of all minerals of the TSF tailings are homogeneous, since the granulometry used to carry the polished sections from the dense fractions is between 150 and 300 μm of the TSF1 and TSF2 tailings and over 75 μm for TSF3 tailings. Some grains consist of complex associations of several sulfides, iron oxide, oxyhydroxide and gangue minerals (Figure 12C,D,H). These minerals are present in the form of mixed grains (Figure 12F,I,J,L,M) in the TSF tailings. Liberated grains of several metalliferous phases were observed like chalcopyrite with irregular forms in the tailings of TSF1 (Figure 12A,B,E) and TSF2 (Figure 12G). The TSF3 tailings shows both liberated grains of chalcopyrite, arsenopyrite and magnetite (Figure 12K,N).

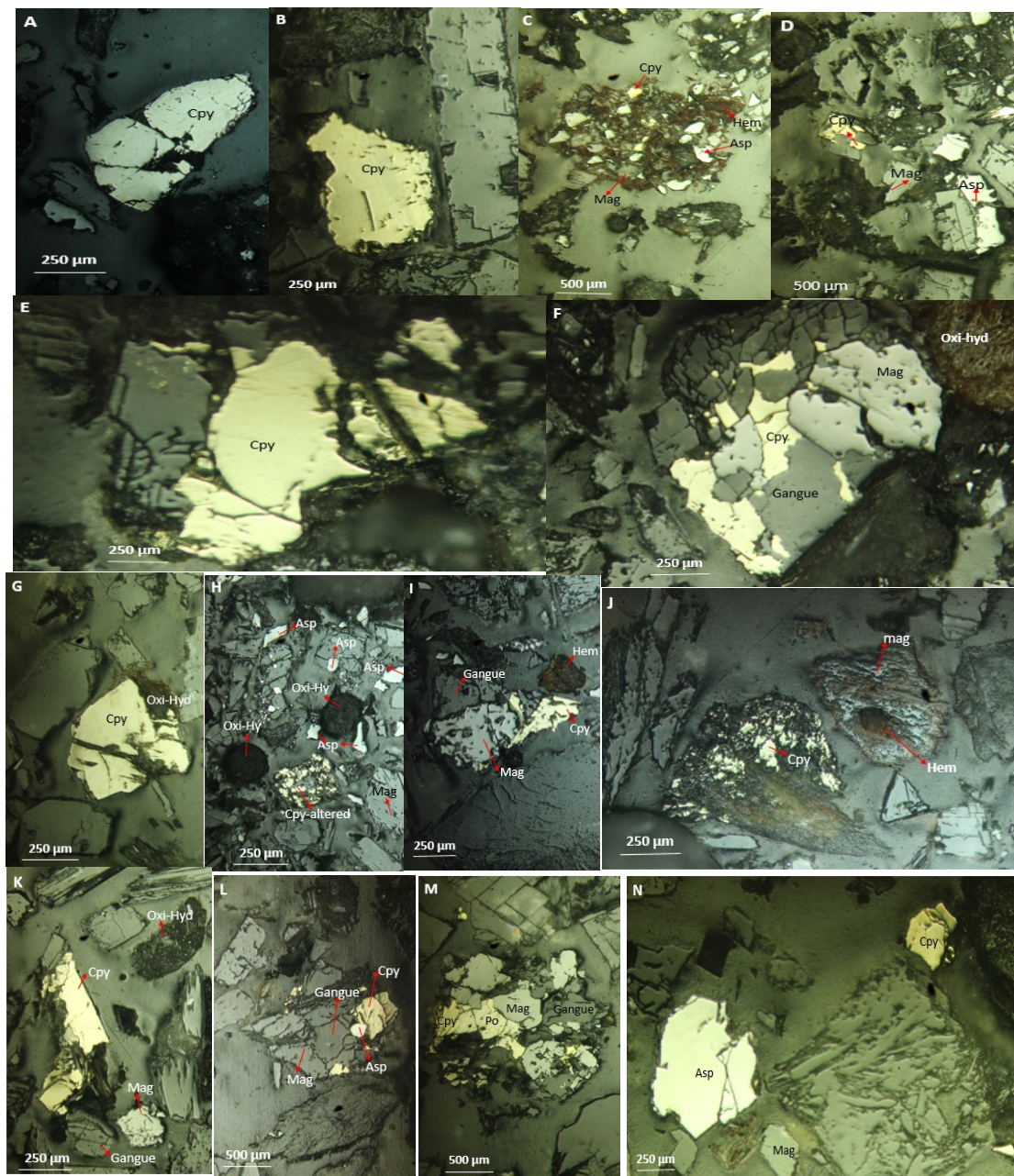


Figure 12. Mineralogy of the TSF1 (A–F), TSF2 (G–J) and TSF3 (K–N) mine tailings determined by metallographic observation (polarized light) of polished sections. Cpy: chalcopyrite, Po: pyrrhotite, Asp: arsenopyrite, Mag: magnetite, Hem: hematite, Oxy-Hyd: oxyhydroxides.

3.4. Chemical Composition

Table 2 summarizes the major and trace elements contents in the different TSF tailings and salt precipitates. The concentrations of major element oxides, Fe_2O_3 , MgO and SiO_2 in all samples are high. Average Fe_2O_3 contents in the tailings are 52.36%, 48.4% and 39.7% for TSF1, TSF2 and TSF3, respectively. These contents are related to the presence of manifold iron bearing minerals in the TSF tailings (magnetite, hematite, chalcopyrite, pyrrhotite, arsenopyrite, stembergite, löllingite, clinosafflorite skutterudite tennantite, siderite, ankerite, clinocllore, biotite, omphacite, actinolite, cummingtonite, anthophyllite). TSF2S and TSF3S also contain high amounts of Fe_2O_3 (25.62% and 27.5%, respectively), which are held in löllingite, clinosafflorite, tennantite, and anthophyllite.

Even though all samples contain high concentrations of SiO_2 and MgO , their concentration is lower with respect to Fe_2O_3 . They come from silicates and carbonates. CaO (1.22–2.99%), Al_2O_3 (0.41–4.99%), MnO (0.51–1.22%), Na_2O (0.11–1.69%), and K_2O (0.06–0.67%) are very rarely present in all TSF tailings. CaO comes from carbonates, silicates, sulfates and arsenates, Al_2O_3 is derived from other major mineralogical sources such as aluminosilicates, while Mn mainly comes from ankerite. Other components such as TiO_2 (0.05–0.17%) and P_2O_5 (0.005–0.15%) are highly depleted.

Table 2. Chemical composition of the tailings and salt precipitates collected in the three TSFs (NA: Not Analyzed, LOI: Loss on Ignition).

Content (%)	Mine Tailings			Salt Precipitates		UCC
	TSF1	TSF2	TSF3	TSF2S	TSF23	
CaO	1.22	1.84	2.2	2.99	1.9	
MgO	12.57	12.78	13.55	15.45	18.55	
SiO_2	8.86	11.66	15.58	17.1	9.37	
Fe_2O_3	52.36	48.4	39.57	25.62	27.5	
Al_2O_3	0.41	2.37	4.57	4.99	1.99	
Na_2O	0.11	0.32	0.69	1.69	1.13	
K_2O	0.06	0.13	0.24	0.67	0.27	
MnO	1.11	1.22	1	0.51	0.69	
TiO_2	0.05	0.07	0.1	0.17	0.05	
P_2O_5	0.1	0.15	0.12	<0.005	<0.005	
LOI	23.15	21.05	22.38	30.78	38.53	
Total	100	99.99	100	99.97	99.98	
S	1.01	1	0.42	NA	NA	
Elements (mg.kg^{-1})						
Au	1.02	0.41	0.28	NA	NA	
As	1407	1577	1210	2114	2453	1.5
Cu	2600	1400	900	896	700	25
Th	410	724	570	407	328	10.7
V	400	647	561	695	216	60
Ni	380	493	459	267	577	20
Co	270	270	240	400	450	10
Se	123	148	141	131	98	0.05
Zn	140	124	103	73	72	71
Pb	100	86	72	47	41	20
Sb	35	35	29	17	16	0.2
Cd	18	14	16	9	12	0.1
Zr	10	9	15	16	13	190
Sr	25	34	62	88	86	350
Ba	200	190	170	NA	NA	550
Cr	30	10	< 5	< 5	< 5	35
Li	< 5	2	3	3	3	20
Mo	< 5	< 5	25	< 5	2	1.5
B	< 5	< 5	< 5	< 5	< 5	15
Be	< 5	< 5	< 5	< 5	< 5	3

Table 2 and Figure 13 illustrate the metallic trace element (MTE) contents in the TSF tailings and in the salt precipitates (TSF2S, TSF3S) compared to their content in the upper continental crust (UCC). These samples are enriched in Cu, As, Th, V, Ni, Co, Se, Sb and Cd and, to a lesser degree, in Zn and Pb, even though they are significantly depleted in Zr, Sr and Ba. The presence of high concentrations of As, Cu, Ni, Co, Sb and Se are linked to the presence of sulfides (chalcopyrite: CuFeS_2 , stibnite: Sb_2S_3 , anilite: Cu_7S_4 , arsenopyrite: FeAsS , paraganajautite: $\text{Bi}_2(\text{Se},\text{S})_3$), arsenides (löllingite: FeAs_2 , skutterudite: $(\text{Co}, \text{Ni}, \text{Fe})\text{As}_3$, clinosafflorite: $(\text{Co}, \text{Ni}, \text{Fe})\text{As}_2$, koutekite: Cu_5As_2 and sulfosalts (tennantite: $(\text{Cu}, \text{Fe})_{12}\text{As}_4\text{S}_{13}$) in the TSF tailings and salt precipitates.

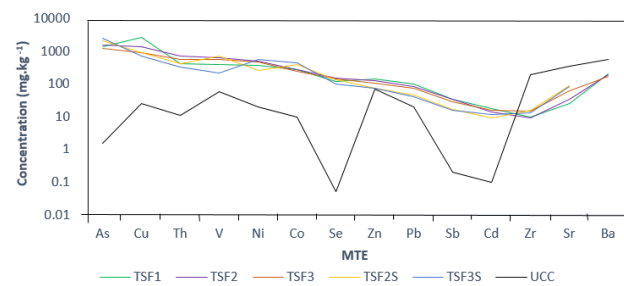


Figure 13. Metallic trace element (MTE) patterns of the mine tailings (TSF1, TSF2, TSF3) and salt precipitates (TSF2S, TSF3S) compared to the upper continental crust (UCC: values are from [80]).

Table 3 shows the concentration of total Fe and Fe in form of oxides (FeO , Fe_2O_3 , Fe_3O_4) and the carbonate content in the TSF tailings. TSF1 (25.6% Fe_3O_4) and TSF2 (20.36% Fe_3O_4) are characterized by high magnetite contents, which will be enriched in the magnetite processing plant by wet low-intensity magnetic separators (WLIMSs). TSF3 was obtained after magnetic separation and indicates the lowest levels of Fe_3O_4 (3.97%). TSF tailings are composed of very low active limestones and very low contents of total carbonates, which may be originally explained by the presence of a carbonated gangue that has been replaced by siderite (ferromagnesian carbonate) and the substitution of Fe by Mg in the crystal lattice of siderite.

Table 3. Fe and Fe oxides and carbonate contents in the TSF tailings (NA: Not Analyzed).

Composition (%)	TSF1	TSF2	TSF3
Fe	36.62	33.85	27.68
FeO	47.11	43.55	35.61
Fe_2O_3	52.36	48.4	39.57
Fe_3O_4	25.6	20.36	3.97
Carbonates	5	6	8
Active limestone	2	2	3

3.5. Environmental Characterization

Static prediction test results (paste pH and ABA) are given in Tables 4 and 5. The pH values, which are 7.77, 7.92, and 8.25 for the TSF1, TSF2, and TSF3 tailings, respectively, are indicative of non-acid-generating materials. Neutral to slightly alkaline pH can be related to the dissolution of neutralizing minerals such as carbonates and silicates [81]. The mechanical agitation of the suspension (liquid/solid) for 24 h shows that pH and conductivity are varying in the ranges of 3.46–3.94 and 57.3–68.9 mS/cm, respectively. Compared to the stirring for 48 h, these results indicate that the pH increases (5.12 to 5.64) while the conductivity decreases (58.7 to 37.4 mS/cm), which implied that there was a higher dissolution of potentially neutralizing minerals under acidic conditions. These results are in accordance with the high NP values during the agitation for 24 and 48 h for TSF1 (48.49 to 60.96 kg CaCO_3 /t), TSF2 (48.58 to 61.17 kg CaCO_3 /t), and TSF3 (49.75 to 61.89 kg CaCO_3 /t) tailings. The AP values were below the NP values for all samples,

equalling 31.56 kg CaCO₃/t, 31.25 kg CaCO₃/t, and 13.12 kg CaCO₃/t. According to [57], the NNP values can be correlated to the intervals 16.93–29.4 kg CaCO₃/t, 17.33–29.93 kg CaCO₃/t, and 36.63–48.77 kg CaCO₃/t, respectively. According to [58], the NP/AP values are in line with the intervals 1.53–1.93 kg CaCO₃/t for TSF1, 1.55–1.96 kg CaCO₃/t for TSF2, and 3.79–4.72 kg CaCO₃/t for TSF3. The authors noted that a prolonged digestion time has allowed dolomite to dissolve completely in the static test at room temperature as opposed to the 24 h test, resulting in more representative NP results. Afterwards, [9,53] demonstrated that the Sobek test, modified by [54], underestimates the NP for samples containing dolomite and ankerite. Based on the mineralogical analysis, the AP values result from sulfide minerals oxidation. Taking into account the low NP of carbonates present in the tailings (dolomite, ankerite, siderite), the NP values are mainly provided by the dissolution of silicate minerals (phyllosilicates, amphiboles), which are mostly present in the TSF tailings as gangue minerals [82]. These silicates are potentially neutralizing minerals at pH = 5, as argued by [83,84]. For the 48 h test, the pH increases and the EC decreases contrary to the 24 h test. This may indicate the precipitation of secondary phases and the retention of metals and metalloids by co-precipitation, adsorption or sorption.

Table 4. Physicochemical characteristics of the static tests of the TSF tailings.

Mine Tailings	pH	Contact Time Liquid/Solid 24 h		pH	Contact Time Liquid/Solid 48 h	
		Conductivity (mS/cm)	NaOH (mL)		Conductivity (mS/cm)	NaOH (mL)
TSF1	3.46	68.9	5.601	5.12	58.7	0.613
TSF2	3.48	67.7	5.566	5.32	54.4	0.530
TSF3	3.94	57.3	5.101	5.64	37.4	0.242

Table 5. Static test results of the TSF tailings.

	Contact Time Liquid/Solid 24 h				Contact Time Liquid/Solid 48 h	
	TSF1	TSF2	TSF3		TSF2	TSF3
S (%)	1.01	1	0.42	1.01	1	0.42
Paste pH	7.77	7.92	8.25			
NP (Kg CaCO ₃ /t)	48.49	48.58	49.75	60.96	61.175	61.89
AP (Kg CaCO ₃ /t)	31.56	31.25	13.12	31.56	31.25	13.12
NNP (Kg CaCO ₃ /t)	16.93	17.33	36.63	29.4	29.93	48.77
NP/AP	1.53	1.55	3.79	1.93	1.96	4.72
Environmental classification of mine drainage	Uncertain	Uncertain	Non-acid generator	Uncertain	Uncertain	Non-acid generator

The criteria NNP and NP/AP adapted from [59] indicated that the acidity generation is uncertain for the tailings from TSF1 and TSF2 and non-acid generating for the tailings from TSF3 (Figure 14). However, based on the neutral pH paste imposed by a silico-carbonated matrix with a high neutralizing potential, the mine drainage is classified as contaminated neutral drainage (CND). However, once produced, CND can carry trace metals such as As, Cu, Ni, Co, Sb and Se, which are considered as potentially toxic elements with respect to the surrounding ecosystems [85].

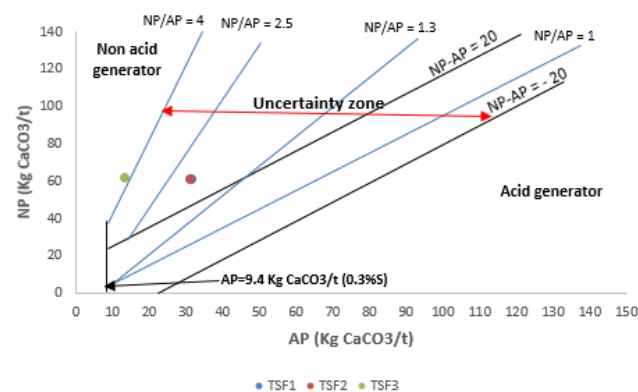


Figure 14. Environmental characterization of the TSF tailings based on NNP and NP/AP for a 48 h test (adapted from [59]).

4. Conclusions

This paper represents the first mineralurgical and environmental characterization of the iron oxide–copper–gold (IOCG) ore of Guelb Moghreïn, Akjoujt Mauritania. Our key findings indicate that the physical properties of the TSF tailings exhibit very low plasticity for (TSF1) and low plasticity for TSF2 and TSF3, revealing silt-sized material characteristics.

Our study shows that the chemical compositions of the TSF tailings and salt precipitates contain high Fe_2O_3 contents. TSF1 and TSF2 tailings are characterized by high magnetite contents, which are recovered in the magnetite processing plant using wet low-intensity magnetic separators (WLIMSs). TSF3, which is obtained after magnetic separation, contains the lowest levels of Fe_3O_4 . We also find that SiO_2 and MgO are present with lower contents in the TSF talings and salt precipitates with respect to Fe_2O_3 . Compared to the UCC, these samples are enriched in Cu, As, Th, V, Ni, Co, Se, Sb and Cd with lesser amounts in Zn and Pb, but they are significantly depleted in Zr, Sr and Ba. After flotation processing, TSF1 shows relatively high levels of Cu (0.26%) and Au (1.02 g/t) that are recovered from a primary ore grading 1.88% for Cu and 1.41 g/t for Au. The geochemical process related to the oxidation of iron sulfides and the dissolution of neutralizing minerals (carbonates and silicates) involves the formation of numerous secondary minerals such as oxyhydroxides, arsenates, sulfates, oxyhalides and halides. Our results also show that the secondary minerals precipitation stems from the formation of highly indurated crusts on the surface of the TSF tailings. At the surface of the tailings, water evaporation results in salt precipitation (hexahydrite, paratacamite, kieserite, cobaltkieserite, aplowite, starkeyite, gypsum, halite). The static mine drainage prediction tests, related to environmental conditions, showed that the bases generated mainly by the dissolution of carbonates and silicates take over the acids which come mainly from the oxidation of sulfides. These tests indicated that for the TSF1 and TSF2 tailings, the AMD is uncertain, while the TSF3 mine tailings is classified as non-acid generating. Thus, and based on the neutral pH paste imposed by a silico-carbonate matrix with a high neutralizing potential, the leaching of the TSF tailings results in contaminated neutral drainage (CND). To further improve and extend our study in order to avoid harmful geo-environmental impacts, we envision developing an approach that optimizes the management of the TSF during mine operation with the objective of facilitating the rehabilitation phase after site closure.

Author Contributions: Conceptualization, N.B.B., F.S. and I.K.T.; Methodology, R.S., F.S. and N.B.B.; Formal analysis, N.B.B., F.S., B.B. and F.M.; Writing—original draft, N.B.B. and F.S.; review & editing F.S., R.S., N.B.B. and M.A.B. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. GPS coordinates of TSF and salts sampling.

Samples	Sampling Points	GPS Coordinates		
		Y	X	Z
TSF1	1130	2184739	559979	116
TSF1	1131	2184654	559732	117
TSF1	1132	2184897	559611	130
TSF1	1154	2184972	559641	128
TSF1	1136	2185022	559757	128
TSF1	1137	2185020	559530	128
TSF1	1138	2185096	559554	131
TSF2	1089 (Salts)	2184704	557167	111
TSF2	1090	2184142	557372	113
TSF2	1128	2183896	556868	110
TSF2	1129	2184496	556611	108
TSF3	1077	2183030	557152	112
TSF3	TSF3-13A	2182904	557125	106
TSF3	1081	2182997	556716	106
TSF3	TSF3-10A	2183172	556521	107
TSF3	TSF3-6	2183243	556830	179
TSF3	1082	2182861	557147	108
TSF3	1083	2182796	557230	105
TSF3	1084	2182218	556781	108
TSF3	1085 (Salts)	2182267	556748	110
TSF3	1086	2182577	556859	109
TSF3	1087 2182445	557135	111	
TSF3	TSF3-9	2182216	556342	104
TSF3	TSF3-8	2182508	556493	114
TSF3	TSF3-11	2182551	556164	107
TSF3	1088	2182811	555983	104

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