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Occurrence, properties and pollution potential of environmental minerals in acid mine drainage

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ABSTRACT

This paper describes the occurrences, the mineralogical assemblages and the environmental relevance of the AMD-precipitates from the abandoned mine of Valdarcas, Northern Portugal. At this mining site, these precipitates are particularly related with the chemical speciation of iron, which is in according to the abundance of mine wastes enriched in pyrrhotite and pyrite. The more relevant supergene mineralogical assemblages include the following environmental minerals: soluble metal-salts, mainly sulphates, revealing seasonal behaviour, iron-hydroxysulphates and iron-oxyhydroxides, both forming ochre precipitates of poorly and well-crystalline minerals.

Pollution potential of the most highly water soluble salts was analysed in order to evaluate the environmental effect of their dissolution by rainfall. Laboratory experiments, carried out with iron and aluminium sulphates, demonstrated the facility to release metals, sulphate and acidity upon dissolution. Regarding the ochre precipitates, composed by several less soluble iron (III)-minerals, the spatial distribution on the nearby aqueous system as well as the proportion of Jarosite, Schwertmannite and Goethite in the mixtures gave information about the halo's contamination promoted by the AMD emerging from the waste-dumps.

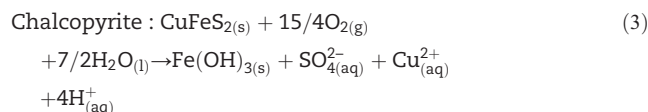
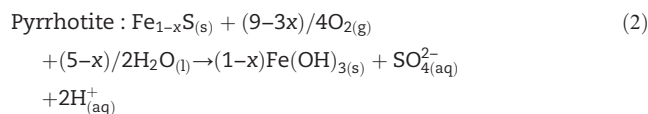
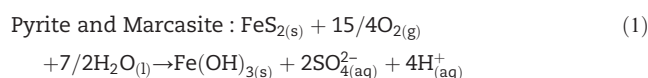
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1. Introduction

Acid mine drainage (AMD) that emerges from sulphide-rich waste-dumps, exposed to weathering processes, is an important focus of environmental impact world widely. There are numerous examples of globally affected mining regions as AMD promotes chemical, physical, biological and ecological interactive effects on the ecosystems (Gray, 1998; Elbaz-Poullichet et al., 2001; Sainz et al., 2004; Valente and Leal Gomes, 2007).

Associated complex chain of biotic and abiotic reactions that involve the oxidative dissolution of sulphides, generating AMD, has been the subject of extensive literature (McKibben and Barnes, 1986; Bhatti et al., 1993; Ritchie, 1994; Evangelou and Zhang, 1995; Nordstrom and Southam, 1997; Keith and

Vaughan, 2000). Eqs.(1) to (3) represent the reactions concerning some of the most common sulphide minerals.



These primordial reactions are often used to demonstrate, in a simplified way, the two main results of mineral–water interac-

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tions involving sulphides: the generation of a highly contaminant effluent (related with the production of acidity, sulphate and metallic dissolution) and the development of supergene or newly formed iron-rich minerals (generically represented by the ferric-hydroxide $\text{Fe}(\text{OH})_3(\text{s})$). These supergene minerals are generically called AMD-precipitates since they appear in the dependence of AMD upon evaporation, oxidation, hydrolysis and neutralization.

The geochemical and mineralogical evolution of the sulphide-rich wastes can be expressed by mild modifications of the primary paragenesis or by profound transformations, which end in new mineralogical structures, some of them with complex compositional and textural patterns, such as iron-rich hardpans (Courtin-Nomade et al., 2003; Gilbert et al., 2003; Lottermoser and Ashley, 2006; Pérez-López et al., 2007). The AMD-precipitates attest the principal evolutionary steps, and, consequently, they reflect stages of momentary stability.

The iron-oxyhydroxides, which are the final terms of such supergene evolution, are well-documented AMD-precipitates (Schwertmann et al., 1987; Bigham et al., 1994; Singh et al., 1999; Bigham and Nordstrom 2000; Kawano and Tomita, 2001; Dold, 2003; Murad and Rojik, 2003; Valente and Leal Gomes, 2005). They occur as ochre mixtures, conferring strong visual impact to the watercourses, which may decide their protagonist role in mining environments. However, the evolution of the sulphide-rich wastes is marked by other newly formed minerals that may involve intermediary terms, such as clay minerals, hydrated salts, metallic oxides, arsenates, carbonates, phosphates and native elements. Often, these minerals come in concert with supergene materials that didn't realized crystalline structure. From these groups, hydrated soluble salts, mainly metal-sulphate minerals, have been deserved careful attention. Although metastable, and therefore ephemeral, they have strong influence on the superficial environ-

ments (Dold and Fontboté, 2001; Hammarstrom et al., 2005; Harris et al., 2003). They also may give valuable information concerning the primary minerals and the composition of the solutions from which they formed as well as about the prevailing equilibrium conditions on waste-dumps.

There are several works that document the role of the soluble sulphates in AMD environments (e.g. Cravotta, 1994; Hudson-Edwards et al., 1999; Nordstrom and Alpers, 1999; Buckby et al., 2003; Sánchez et al., 2005), some of them testifying the discovery of new minerals (e.g. Jambor and Boyle, 1962). A detailed review that emphasises the relevance of metal-sulphates, from a variety of perspectives including paragenetic relations and climate control, is provided by Alpers et al. (2000).

Supergene materials from sulphide mineral oxidation have great relevance in environmental mineralogy, concerning their role controlling pollutants in contaminated environments (Cotter-Howells et al., 2000; Hochella, 2002; Vaughan et al., 2002). Both, metal soluble-sulphates, occurring as efflorescences, and iron (III)-minerals that form ochre precipitates, are key-examples of environmental minerals in the acceptance given by Valsami-Jones (2000). The firsts are worthy of this mention because they are highly soluble hosts of pollutants; their role in the release of metals and acidity, upon dissolution by rainfall, is well documented (Buckby et al., 2003; Gomes and Favas 2006; Alpers et al., 1994; Frau, 2000). The second group comprises less soluble hosts, which are often poorly crystalline phases with large surface areas. Consequently, they reduce the mobility of toxic elements, including metals and metalloids, which are retained by adsorption and coprecipitation (Smith et al., 1998; Carlson et al., 2002; Hammarstrom et al., 2003; Lottermoser, 2003). The ability to indicate, sometimes in an expeditious way, the prevailing conditions in the contaminated environment, in

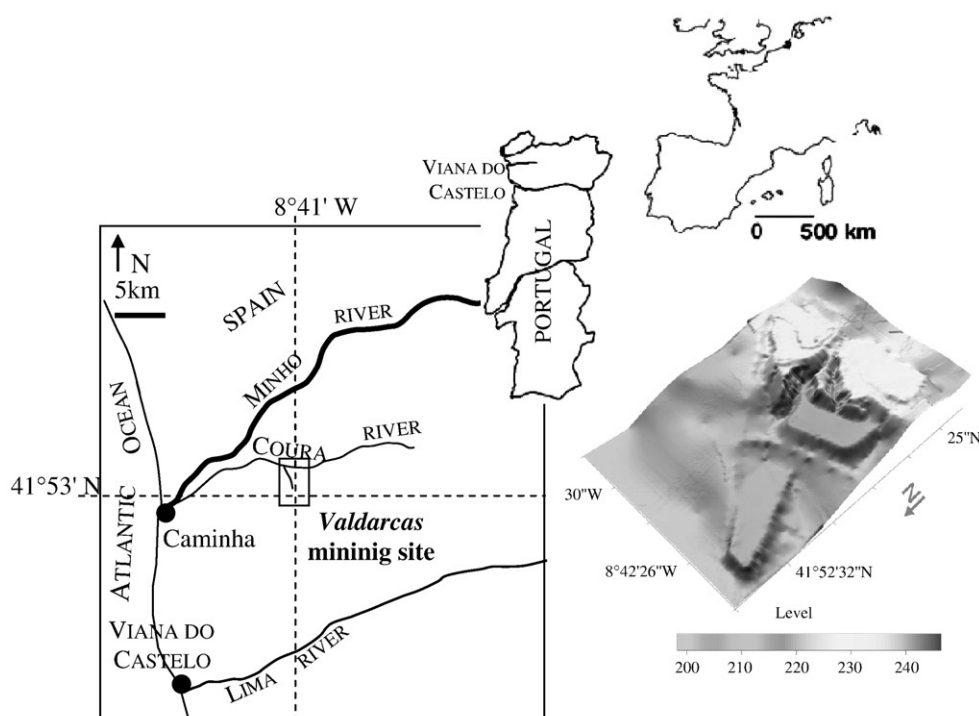


Fig. 1 – Location of Valdcas mining site in Northern Portugal and surface map of the waste-dumps.

Table 1 – Most typical minerals from the ore deposit that were also identified at the waste-dumps (Valente, 2004)

Silicates	Carbonates and phosphates	Ore	Sulphides	Trace minerals
Actinolite				
Tremolite				
Wollastonite			Pyrrhotite	Lollingite
Plagioclase	Calcite		Pyrite	Bismuthinite
Idocrase	Siderite	Scheelite	Marcasite	Bismut
Grossular	Apatite	Wolframite	Sphalerite	Gersdorffite
Epidote		Ferberite	Arsenopyrite	Tetrahedrite
Diopside			Chalcopyrite	Cubanite
Quartz				Mackinawite
Muscovite				
Chlorite				

which they are stable, gives another sense to the specific mention of environmental minerals.

This paper documents the supergene environmental minerals generated in the dependence of the AMD conditions, at Valdarcas mining site (Northern Portugal). It provides an inventory of soluble salts and of less soluble iron-rich minerals identified at the waste-dumps and in the nearby aquatic system. Morphologic and composition aspects as well as paragenetic relations are presented for typical minerals and assemblages.

The environmental relevance of both types of AMD-precipitates is shown in two perspectives: 1) the pollution potential of typical soluble sulphates, which was demonstrated by laboratory dissolution experiments and 2) the ability of ochre precipitates to reveal the AMD conditions and therefore to act as mineralogical indicators of AMD.

2. Site description

Valdarcas mine is located in Northern Portugal, in a region where metal mining has large and long tradition (Fig. 1). Wolframite and scheelite were exploited for tungsten in a skarn ore deposit, which is rich in sulphides. The most intensive works took place underground, between the fifties and eighties, and have left about 310,000 m³ of processing wastes that have resulted mainly from grinding (grain size of about 2 mm) and from minor treatment by flotation.

Table 1 lists the minerals, from the ore deposit, that compose the mine wastes. Besides ore minerals, gangue comprises three main classes that display contrasting geochemical behaviour when exposed to weathering conditions at the waste-dumps. They are by decreasing order of abundance: sulphides (promoting acidity) > silicates (slow consumers of acidity) > carbonates (fast consumers of acidity). The sulphides are mainly represented by massive pyrrhotite and pyrite (about 95% of the sulphide mass) (Valente, 2004). Therefore, the mine wastes consist primarily of the most reactive and acid producing sulphide phases (Bhatti et al., 1993; Kwong and Lawrence, 1994; Plumlee and Nash, 1995; Jambor and Blowes, 1998).

Mine wastes, carrying these minerals, were accumulated in three major impoundments built without drainage control, which went far towards the strong physical instability. Mechanisms of water erosion, such as sheet, rill and gully erosion, have created impressive marks, like the two deep gullies illustrated in Fig. 1. The topographic irregularities are important because they control the terrain aspect and terrain slope. These, by their turn, allow the development of micro-climate conditions that must be considered when studying the occurrences of supergene minerals.

For decades, AMD has emerged from the waste-dumps exposed to weathering processes. Nowadays, marks of environmental impact still persist on the nearby aqueous system, mainly due to the discharge of acidic effluents in a small stream (Poço Negro creek), and then in the Coura river (Figs. 1 and 2).

Rainfall is the principal water supply for mineral–water interactions involving the mine wastes at Valdarcas. The region has a temperate climate and is located in the rainiest province of Portugal. Monthly precipitation range from 625 mm to 1455 mm, values corresponding respectively to the dry semester (from April to September) and to the wet semester (from October to March, with January as the rainiest month). Average annual temperature is 12.5 °C, being January also the coldest month (mean 9.4 °C), while in the summer, July and August present the highest temperatures (mean 25.7 °C) (www.inag.pt). Measurements at the waste-dumps for relative humidity gave maximum in winter (80 to 100%) and minimum (<20%) between June and August.

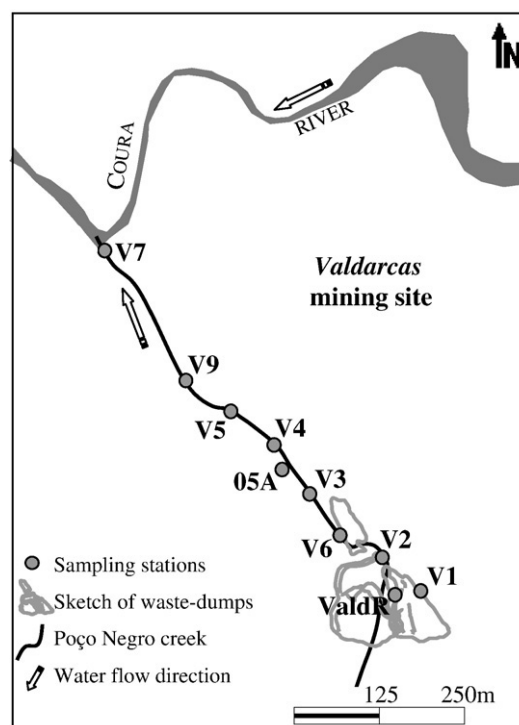


Fig. 2 – Location of the sampling stations, for ochre precipitates and AMD, at the waste-dumps and along the main effluent channel (Poço Negro creek).

3. Methods

Sampling of minerals and water (AMD) took place over about six years of field work (between January 2001 and February 2007), dedicated to construct an extensive and diversified database capable to assist the AMD modelling efforts at this mining site. Several campaigns were carried out, ensuring a minimum of four visits per year in order to represent the climatic seasonality.

3.1. Mineral sampling and analysis

For soluble sulphates, sampling fell on the waste-dumps, covering the plain surfaces, the two main gullies illustrated in Fig. 1 and other temporal varying terrain irregularities, in such a way to represent different conditions of sun exposure, humidity and topography. Samples were also collected along the Poço Negro creek, whenever their presence was detected.

As far as iron ochre mixtures are concerned, since they are ubiquitous, samples were grabbed from fixed locations at the waste-dumps and at the Poço Negro creek streambed, obeying to the sampling stations represented in Fig. 2.

Samples were stored in closed plastic bags and transported to the laboratory soon after the collection, in order to prevent mineralogical changes.

Mineralogical composition was analysed by X-ray powder diffraction (XRD) with a Philips X'pert Pro-MPD diffractometer, using Cu-K α radiation. Sample preparation procedures and the appropriated XRD conditions for these kinds of samples, in particular leading with low crystallinity, fine grain size, impurity of the assemblages and high hydration states are described in Valente (2004). Fig. 3 shows the iterative procedure used to refine samples and to achieve mineral identifications. Specifically with respect to the most instable salts, binocular microscopy and XRD were performed immediately after arriving to the laboratory, and the samples were reanalyzed to evaluate aging effects.

Scanning electron microscopy (on carbon or gold coated samples), with a LEICA S360 microscope, combined with an energy dispersive system (SEM-EDS), allowed the study of morphological and compositional aspects. In some cases, it helped in the identification of complex assemblages and of amorphous materials.

3.2. Characterization of AMD

AMD was characterized through samples collected at the sampling stations indicated in Fig. 2 (the same stations as for ochre precipitates). This work presents the hydrochemical characteristics of samples collected at two sampling stations representing discriminative environments: at the waste-dump surface (ValdR) and downstream in the Poço Negro creek (V7). The pH range is also provided for the rest of the stations. At V7 water flow is permanent; at ValdR water is ephemeral and then sampling was dependent on ponded water availability. A complete characterization of the system, including all the sampling stations, is provided in Valente and Leal Gomes (2008).

pH, electric conductivity (EC), redox potential and temperature of the water were measured in the field with a multi-parameter meter (Orion, model 1230). The following Orion probes were used: combined pH/ATC electrode Triode ref. 91-07 W, conductivity cell DuraProbe ref. 0133030 and a redox combination electrode ORP ref. 96.78. Before use, electrodes were calibrated and/or tested for accuracy, according to the manufacturer's instructions. Direct measurements of redox potential were converted relative to the hydrogen electrode (EH), using standard voltages from the manufacturer.

After collection, samples were immediately refrigerated, transported in polyethylene bottles kept in the dark and stored at 4 °C until analysis. Laboratory analyses were performed for

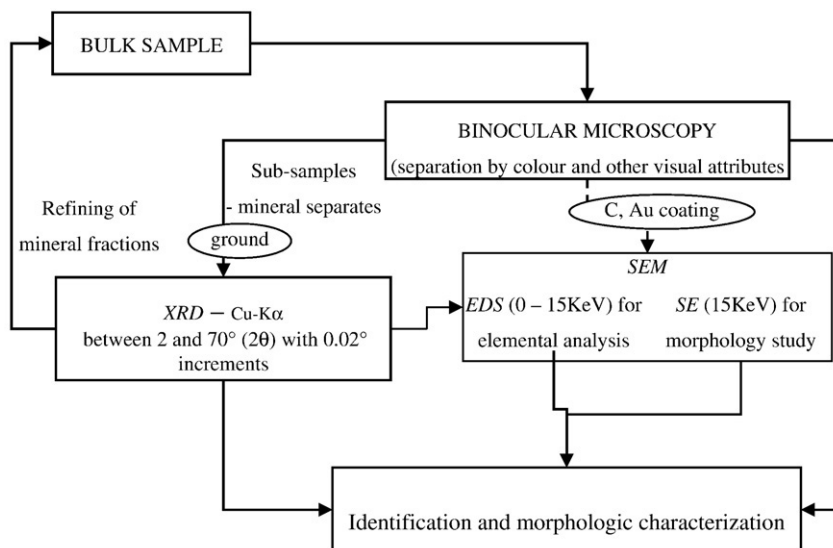


Fig. 3 – Iterative protocol for mineral identifications in soluble sulphate assemblages. XRD – Powder X-ray diffraction; SEM – Scanning electron microscopy; SE – Secondary electrons.

fluoride and chloride by ion chromatography (IC) with suppressed conductivity detection (761 Compact IC Metrohm). Sulphate was measured by turbidimetry and total acidity by volumetric determination (Standard methods for water analysis reference 4500E and 2310B, respectively). Inductively coupled plasma-atomic emission spectroscopy (ICP-AES) and atomic absorption spectroscopy (AAS) were used for metals. IC, ICP-AES and AAS analyses were preceded by sample filtration through 0.2 μm pore-diameter cellulose ester membrane filters, carried out immediately after arriving to the laboratory. For the analysis of metals, filtration was followed by acidification with HNO_3 65% *suprapur* Merck.

3.3. Laboratory dissolution experiments

The dissolution of soluble sulphates was simulated in the laboratory, using air-dried materials collected at the waste-dumps. Two typical efflorescences from Valdarcas waste-dumps were submitted to dissolution in ultra-pure water: samples carrying hydrated iron-sulphates in the assemblage Melanterite ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) + Rozenite ($\text{FeSO}_4 \cdot 4\text{H}_2\text{O}$) and pure samples of the mixed iron and aluminium-sulphate halotrichite ($\text{FeAl}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$). The experiments were performed by the following protocol:

- Temperature and dissolution conditions: room temperature (20 °C) with constant slow agitation;

- Solution: ultra-pure water from Millipore system, with electric conductivity of 0.1–0.4 $\mu\text{S}/\text{cm}$ (50 to 100 mL of solution, depending on the amount of available sample);
- Salt concentrations – 0.4; 2.0; 20; and 250 g/L;
- Duration of experiments – 15 min;
- Control parameters: the acid producing potential was determined from pH continuous measurements; the metals Mn, Fe, Al, Cu, Zn, the metalloid As, as well as the anions Fluoride, Chloride and Sulphate were analysed in the final solution (using the same methods as for AMD analyses).

4. Results and discussion

Table 2 records the supergene materials identified at the waste-dumps and downstream in the main effluent channel (Poço Negro creek). Information about abundance and seasonal persistence is included. These materials define two main modes of occurrence:

- Efflorescences (EFL) – products of evaporative processes composed by soluble metal salts, appearing monomineralic or as mineral assemblages;
- Ochre precipitates (OP) – products of oxidation and neutralization comprising relatively insoluble iron(III)-bearing minerals, often as mixtures, displaying ochre colours.

Table 2 – AMD-precipitates identified at Valdarcas

Mineral	Ideal formula	Abundance/distribution	Persistence (20 < %HR < 98)	Principal mode of occurrence
Melanterite	$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	++++/L	E	EFL→CRUS
Siderotil	$\text{FeSO}_4 \cdot 5\text{H}_2\text{O}$	++/L	E	EFL
Rozenite	$\text{FeSO}_4 \cdot 4\text{H}_2\text{O}$	++++/A	E	EFL→CRUS
Mallardite	$\text{MnSO}_4 \cdot 7\text{H}_2\text{O}$	++/L	E	EFL
Gunningite	$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$	+/L	E	EFL
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	+++++/A	P	EFL→CRUS
Starkeyite	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	++/L	E	EFL
Alunogen	$\text{Al}_2(\text{SO}_4)_3 \cdot 17\text{H}_2\text{O}$	+++/L	E	EFL
Meta-alunogen	$\text{Al}_2(\text{SO}_4)_3 \cdot 12\text{H}_2\text{O}$	+/L	E	EFL
Khademite	$\text{Al}(\text{SO}_4)\text{F} \cdot 5\text{H}_2\text{O}$	++/L	E	EFL
Rostite	$\text{Al}(\text{SO}_4)\text{OH} \cdot 5\text{H}_2\text{O}$	++/L	E	EFL
Tamarugite	$\text{NaAl}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$	+/L	E	EFL
Halotrichite	$\text{FeAl}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$	+/L	E	EFL→CRUS
Jarosite	$\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$	+++++/A	P	OP→CRUS
Schwertmannite	$\text{Fe}_8\text{O}_8(\text{SO}_4)(\text{OH})_6$	+++++/A	P	OP→CRUS
Goethite	FeOOH	+++++/A	P	OP→CRUS
Ferrihydrite	$5\text{Fe}_2\text{O}_3 \cdot 9\text{H}_2\text{O}$	+/L	P	CRUS
Lepidocrocite	$\gamma\text{-FeOOH}$	+/L	P	CRUS
Calcite	CaCO_3	++/A	P	CRUS+EFL
Sulphur	S	+/L	E	EFL
Kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	+++/A	P	CRUS
Esmectite	$(\text{Na}, \text{Ca}_{0.5})_{0.7}(\text{Mg}, \text{Fe}, \text{Al})_6(\text{Al}, \text{Si})_8\text{O}_{20}(\text{OH})_4$	+++/A	P	CRUS
AMD-precipitates without crystallinity				
Silica	SiO_2	+++/A	P	CRUS
Iron phosphate	FePO_4	++/L	P	CRUS
Iron sulphate	FeSO_4	++/A	E	OP
Calcium carbonate	CaCO_3	++/L	P	CRUS

EFL – Efflorescences; OP – Ochre precipitates; CRUS – Crusts from cementing processes; P – Persistent (present in whole range of humidity); E – Ephemeral (present only in dry conditions); L – restricted to the waste-dumps; A – spread out downstream in the creek. Qualitative abundance: rare (+) to very abundant (++++).

As secondary precipitation proceeds, salt efflorescences and ochre precipitates may develop encrustation processes. In that case, they lead to thick salt crusts or iron-rich crusts respectively. When well-developed, such encrusting products act like supergene cement for primary and secondary minerals. Some materials, like lepidocrocite, were observed only inside solid crusts (CRUS) while others were detected only as powdered efflorescences (ex: mallardite) or as relatively loosely ochre precipitates (amorphous iron sulphate). Minerals, such as melanterite and gypsum are typically involved in encrustation processes, and, therefore, it is possible to observe the evolutionary process (EFL→CRUS).

The mineral classes can be organized in accordance with abundance, in the following manner:

oxyhydroxides and sulphates > silicates (clay minerals) > carbonates > native element.

Regarding chemical composition there are species of alkali and alkaline earth metals, transition metals and aluminium. Precipitation of calcium occurs mainly as gypsum and calcite. Calcite is rarely individualized in macroscopic samples at the waste-dumps, being detected mainly inside consolidated crusts. It can also be observed, as efflorescences, over coarse fragments of waste rock from mining operations that are exposed around the mining site. Gypsum is very abundant and omnipresent, even in wet conditions.

Concerning iron sulphates, the inventory includes mainly simple hydrated salts with ferrous iron. Rozenite and melanterite are the more common soluble iron minerals, occurring as efflorescences. Trivalent iron was only found in relatively insoluble oxyhydroxides (ex: goethite) and hydroxysulphates (ex: jarosite).

Aluminium forms a variety of soluble sulphates, including alunogen, rosite-khademite and halotrichite. Zinc and man-

ganese have also mineralogical expression, although rare, by means of the heptahydrates gunningite and mallardite, respectively. There are also amorphous materials composed by silica, iron-oxyhydroxides and iron phosphates.

4.1. Efflorescences of soluble sulphates

Efflorescent mineralogy is formed in dry conditions by precipitation as AMD become more concentrated by evaporation. Efflorescences comprising the soluble sulphates are often complex mixtures, concerning mineralogy and morphology.

4.1.1. Mineralogy and morphology

Efflorescences were more often observed in complex miscellaneous assemblages and rarely as single phases. Figs. 4–6 show XRD patterns for some common or representative identified assemblages.

Gypsum is the most abundant mineral that occurs as efflorescences. It is an exception since it grows frequently as monomineralic rosettes or as spherical concretions, often cemented by jarosite (Fig. 7 a) and b)). However, at the same time, gypsum was detected in the major saline polymineralic aggregates.

Rozenite is also a very abundant mineral at Valdarcas (Fig. 7 c) and d)). It occurs frequently in association with melanterite and or gypsum. In fact, Rozenite+Melanterite is one of the most well represented assemblages, developing botryoidal or reticulated aggregation (Fig. 7 e)).

Individually, rozenite appears as white rosette or as whitish silky powder, while melanterite forms green or blue-green globules (Fig. 7 f)) with humid-touch. Encrustations, characterized by roughness, were observed during prolonged dry periods. The variety of colour shades, observed in the field images, is due to the impurity of the aggregates and it is consistent with the mineralogical evolution of these salts. It is

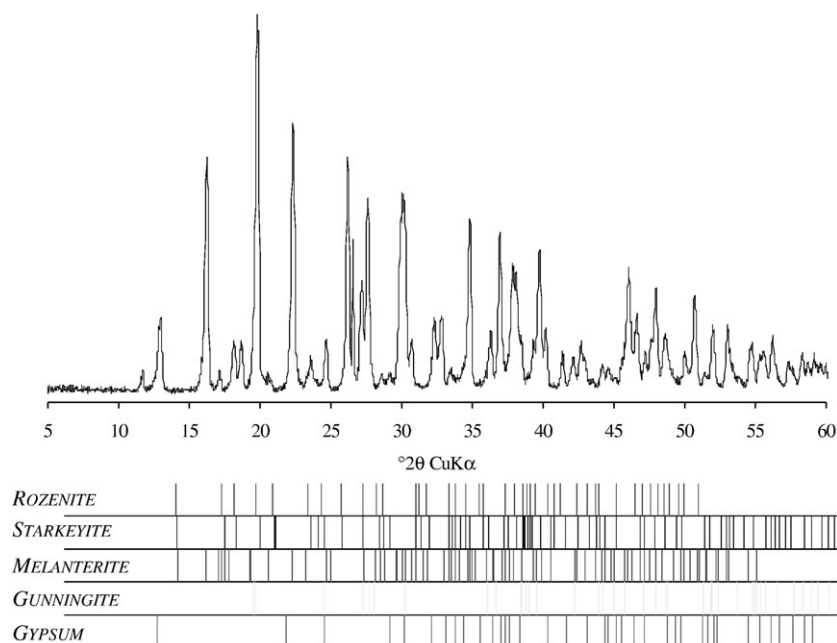


Fig. 4 – XRD pattern from a complex assemblage including the abundant iron sulphates (rozenite and melanterite) and the more rare zinc (gunningite) and alkaline earth metals (starkeyite and gypsum) sulphates. Pattern peaks from ICDD.

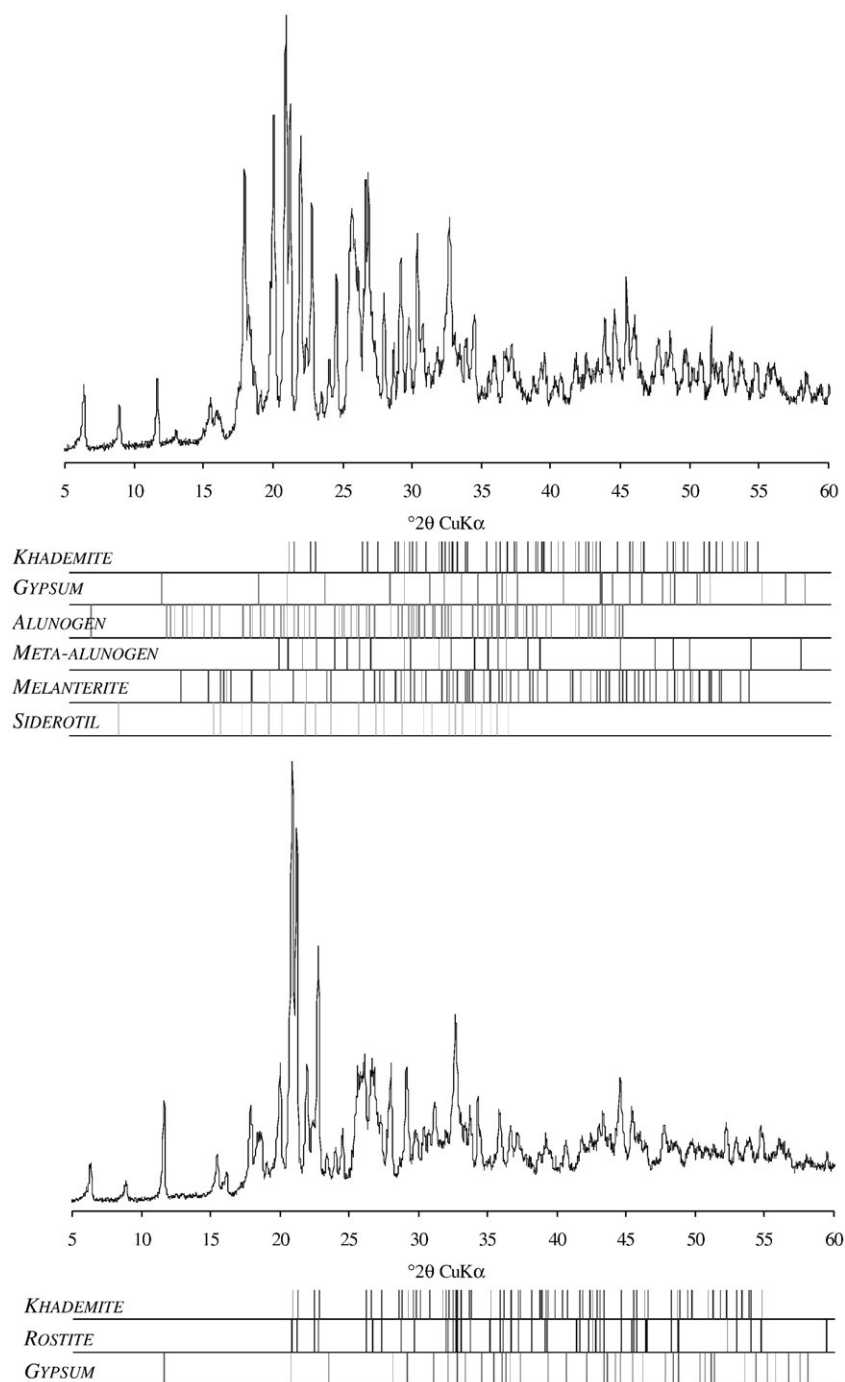


Fig. 5 – XRD patterns of efflorescences carrying several Al-sulphates. Pattern peaks from ICDD. Powder X-ray diffraction; SEM – Scanning electron microscopy; SE – Secondary electrons.

known from literature that melanterite weathers by dehydration and oxidation to form rozenite (white) and oxyhydroxides (yellow-ochre) (Nordstrom and Alpers, 1999; Chou et al., 2002; Jerz and Rimstidt, 2003). Such assemblages as well as the relationship with aluminium sulphates were confirmed by observations around the small channel illustrated in Fig. 7 g). It represents a microenvironment controlled by topographic irregularity and by the emergence of acidic effluent. The slow flow of AMD allows the sequential precipitation of several soluble minerals. Melanterite and Al-sulphates (such as

alunogen and khademite) prefer the interior sheltered portion of the channel, with higher humidity, whereas rozenite was identified at the most sunlight exposed and consequently driest areas.

Al-sulphates were rarely found without melanterite, forming intergrowths that make nearly impossible to isolate single phases. This is confirmed by SEM study (Fig. 8). In these assemblages, foliated crystals of Al-sulphates form radiated aggregates that grow over melanterite, which by its turn presents well developed prismatic crystals. Halotrichite was

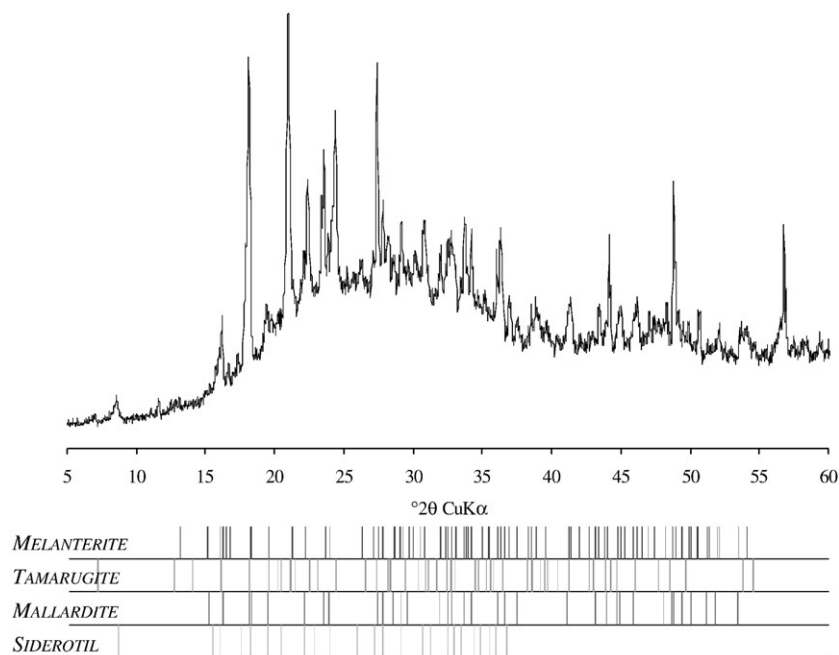


Fig. 6–XRD pattern from a complex assemblage including iron (melanterite and siderotil), manganese (mallardite) and aluminium sulphates (tamarugite). Pattern peaks from ICDD.

found with typical acicular habit and can be seen as an exception because it forms pure concretions. This mineral is more abundant at the skarn pits resulted from open pit mining, where it grows as white masses, in coexistence with amorphous spherical iron-sulphate.

Although rare, siderotil was detected in assemblages carrying melanterite and aluminium sulphates (Fig. 6). When compared with the more common Rozenite+Melanterite assemblage, the Melanterite+Siderotil showed a much intense blue colour, which may be reflecting the incorporation of copper by melanterite, like it was demonstrated by Jambor and Traill (1963). At Valdearcas it wasn't detected the coexistence of the three minerals melanterite, siderotil and rozenite, which is consistent with the results of the cited authors that demonstrated the preferential evolution of copper-bearing melanterite by dehydration to siderotil, in spite of rozenite under the same conditions.

The assemblage Rozenite+Gypsum+Sulphur was found to form well-crystallized aggregates. They occur as very fine grained yellow-coloured powders, often fairly thick (1–2 cm), characterized by softness and by intense sulphur odour. SEM study has revealed that native sulphur occurs with euhedral crystals dispersed over the sulphate efflorescences.

4.1.2. Distribution, seasonal behaviour and paragenesis

Soluble sulphates were abundantly observed at the waste-dumps and rarely along the Poço Negro creek. Here, gypsum and rozenite were the only identified soluble salts. They occur at the margins of the creek, episodically, during evaporative periods. Fig. 9 shows the distribution of the sulphate-mineral assemblages over the waste-dumps surface, for winter and summer conditions.

During summer, efflorescent blooms of gypsum and rozenite were observed as thick accumulations that cover

great extensions of the exposed surfaces. Occasionally, during the most prolonged dry periods, native sulphur joins to this assemblage. The way the well-developed sulphur crystals appear over sulphates suggests that sulphur belongs to a latest stage of slow deposition relative to sulphate minerals. Melanterite and Al-sulphates were only observed in narrow sheltered areas, in the presence of remnant effluent.

In winter, gypsum rosettes grow even on the most exposed vertical slopes of the waste-dumps in accordance with the relative low solubility of this sulphate. Highest mineralogical diversity was observed during fairly long-lasting evaporation periods (one or two weeks) that succeed intensive rainfall periods (often in February). In these conditions, melanterite was the first Fe-sulphate to be identified, followed by the Al-sulphates. If evaporation conditions were persistent, it was possible to observe the assemblage Rozenite+Melanterite (major rozenite), at the most sunny exposed conditions. These field observations, combined with the morphologic features, indicate that Al-sulphates precipitate after melanterite. Fig. 8 shows Al-sulphates over melanterite crystals, suggesting that the latest deposition of aluminium may be the result of iron depletion in the solution.

Interpretation of the occurrences and distribution justify summarizing the following remarks:

- There are microenvironments for mineral precipitation, related with topographic irregularities that have allowed a variety of exposure conditions to the climate elements; for instance, erosion has created cavernous shelters, even at the most vertical and climate exposed slopes, that ensure the persistence of the most soluble salts (melanterite and Al-sulphates) during winter (protecting them from dissolution) and during summer (protecting them from desiccation).

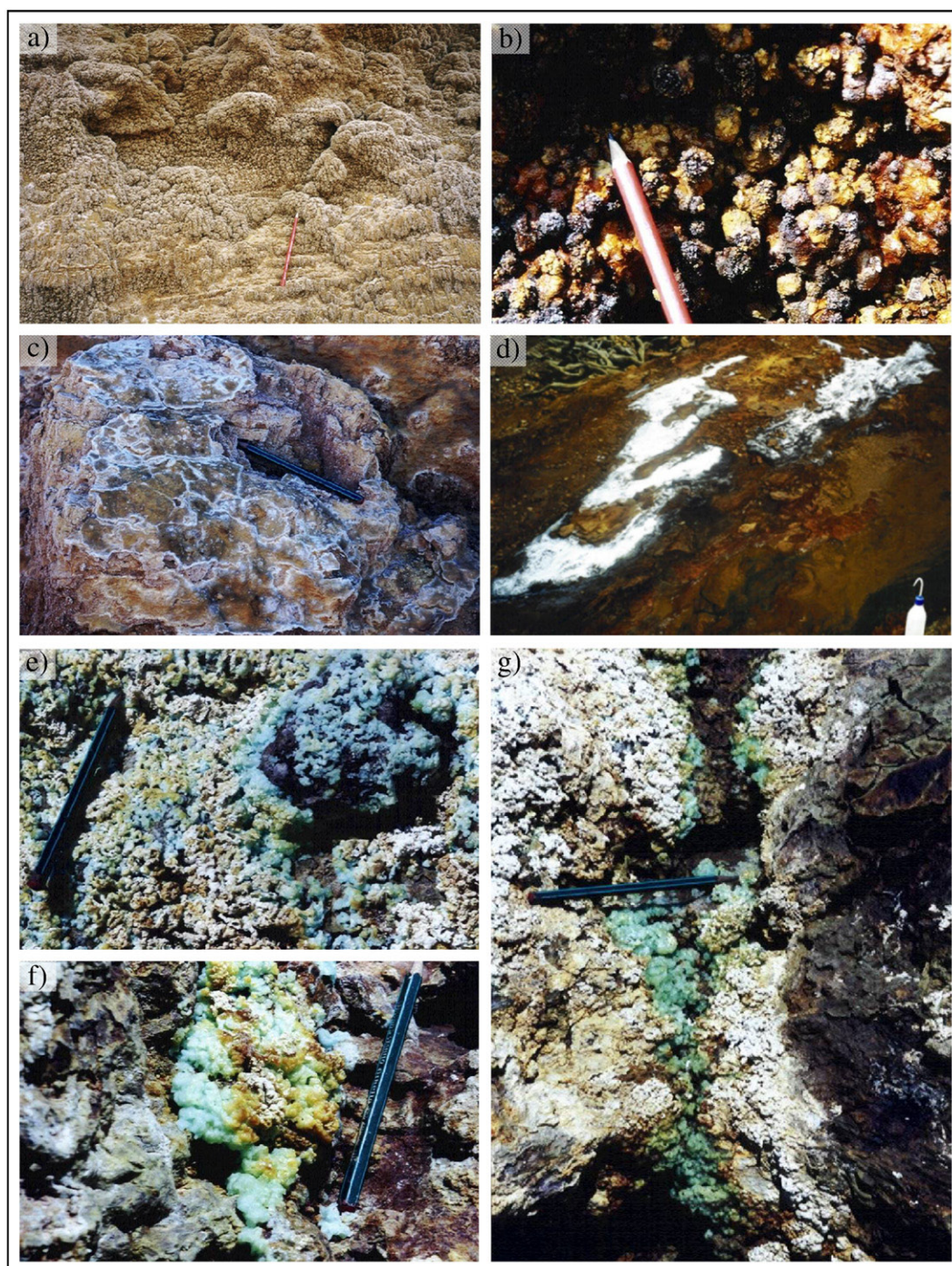


Fig. 7 – Field images of representative sulphate efflorescences. a) Fragile white rosettes of gypsum; b) Gypsum rosettes cemented by jarosite; c) Rozenite in plaques on desiccation fractures network; d) Powdered efflorescences of Rozenite+Gypsum+Sulphur; e) General aspect of the efflorescences including rozenite and melanterite with minor oxyhydroxides; f) Detail of melanterite (green globules) and of its weathering products rozenite (white) and oxyhydroxides (brown); g) Microenvironment of salt precipitation controlled by humidity conditions comprising rozenite+melanterite+Al-sulphates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Melanterite occurs preferably near the most acidic seepages, indicating the proximity to its paragenetic precursors (mainly pyrrhotite); Table 3 shows the composition of the effluent at ValdR, which represents the most acidic AMD, from which this salt precipitates;

- At the most acidic seepages, melanterite precedes the Al-sulphates; this sequence suggests that the latest deposition of the aluminium minerals is controlled by high Al:Fe ratios, resulting from iron depletion in the solution; this is in accordance with the paragenetic sequence observed by

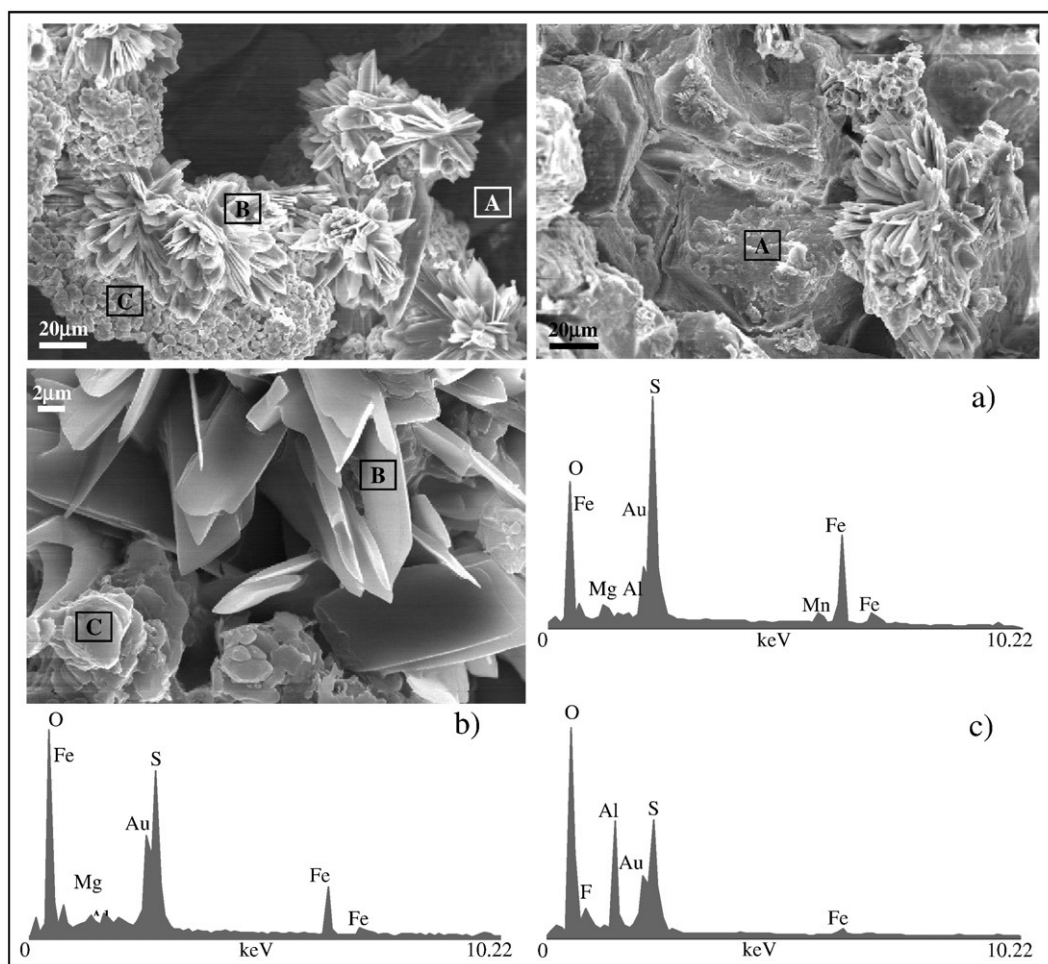
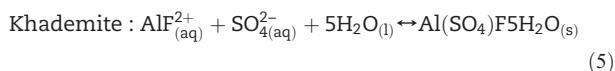
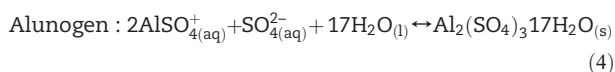


Fig. 8–Morphology of typical intergrowth between melanterite and Al-sulphates (probably alunogen e khademite). SEM (SE) images and respective EDS spectra for representative samples.

Jerz and Rimstidt (2003) in an abandoned mine located in Blue Ridge province in south-western Virginia;

- Eqs. (4) and (5) describe two possible pathways for the precipitation of Al-sulphates from the chemical evolution of the sulphate and fluoro-complexes that may exist in solutions like AMD at ValdR (Table 3):



- Rozenite grows as efflorescent blooms, formed directly by evaporation of diluted AMD solutions, or than it results from melanterite dehydration at the most acidic seepages.
- The assemblage Rozenite+Gypsum+Sulphur is only stable at the summer driest conditions;
- Gypsum was observed in the entire range of temperature and humidity.

4.1.3. AMD and pollution potential

Table 3 presents the composition of the AMD at two selected sites, represented in Fig. 2. ValdR is located at the waste-

dumps and coincides with the furthestmost soluble salt diversity. V7 is located at the main effluent channel, approximately 500 m downstream from the base of the waste-dumps.

ValdR presents the lowest pH values and the higher levels of the generality of pollutants, except sodium and potassium. These properties are in accordance with the nature of the mineral–water interactions that prevails here. In fact, ValdR represents the result of slow water percolation in the interior of the waste-dumps. This allows the dissolution of silica and other chemical species, which are solubilised even from more stable minerals such as the silicates. Therefore, the contact with the parent sulphides explains the highly acidic effluent that is also very rich in sulphate and metals. The exceptions noted for sodium and potassium may be related with the strong precipitation of jarosite, which retains efficiently these elements.

On the other hand, V7 represents more oxidized conditions and also the effect of dilution and other natural attenuation processes that occur as the creek flows away from the waste-dumps. This is well noted for metals and arsenic, given that levels are fairly lower at V7. In that condition, the chemical potential to precipitate metal soluble salts is quite lower, and, consequently, gypsum and rozenite are the only evanescent sulphates, rarely observed. Along the creek, the physical-chemical conditions impose the oxidation of iron and the

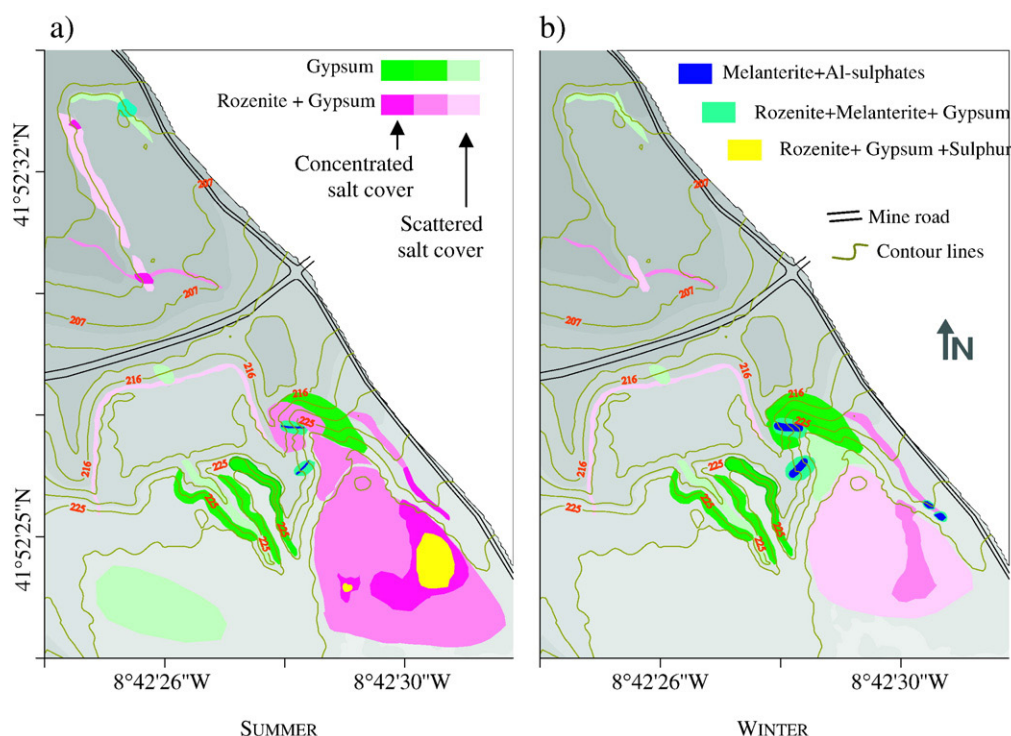


Fig. 9 – Cartographic distribution of the most typical sulphate-minerals in extreme seasonal conditions. a) summer; b) winter.

precipitation of the iron(III)-bearing minerals presented in Table 2. Consequently, pollutants are being removed upstream by these minerals, as they retain iron, by incorporating it in their structure, and other metals and arsenic, by adsorption.

The ability of the identified soluble salts to produce acidic and metal-rich solutions was demonstrated through the experimental dissolution of selected typical samples. Fig. 10 shows the evolution of pH during the dissolution of halotrichite and of

mixed Melanterite+Rozenite samples at the same conditions (concentration: 20 g/L; 20 °C).

As it was observed by Frau (2000) during pure melanterite dissolution, a low and stable pH value was promptly established for both experienced samples. However, halotrichite shown higher acidic potential, with pH dropping from 5.7 to 3.2 in the first 2 min. These results are reflecting the reactions described by Eqs. (6) to (9), which display the acid generation through the release

Table 3 – Composition of AMD at two different selected sites

	Sampling station					
	ValdR (n=15)			V7 (n=24)		
	Mean	Min	Max	Mean	Min	Max
pH	2.53	2.07	3.26	3.10	2.70	3.73
Temperature (°C)	14.5	9.0	22.2	14.2	8.3	21.6
Electric conductivity (μS/cm)	4970	1552	11870	866	525	1079
EH (mV)	730	535	836	737	637	790
SO ₄ ²⁻ (mg/L)	5880	833	21630	327	167	460
F ⁻ (mg/L)	173	15.1	835	3.83	1.30	5.16
Acidity(mg/L CaCO ₃)	3943	1252	7788	241	98.0	372
Fe (mg/L)	2143	147	15000	48.6	1.66	160
Mn (mg/L)	204	3.20	2300	7.00	3.30	9.50
Cu (mg/L)	17.4	3.26	55.0	0.061	0.03	0.11
Zn (mg/L)	8.71	0.42	45.0	0.22	0.15	0.27
As (mg/L)	9.61	0.043	57.0	0.032	0.0006	0.30
Ca (mg/L)	257	63.6	750	28.8	14.0	39.0
K (mg/L)	1.32	0.30	4.90	1.29	0.95	2.39
Al (mg/L)	3735	39.4	42000	17.4	12.0	29.5
Na (mg/L)	2.85	0.50	5.70	5.74	4.58	6.25
SiO ₂ (mg/L)	56.2	12.5	93.5	19.5	15.0	25.5
Mg (mg/L)	43.2	5.02	107	4.82	4.25	5.66

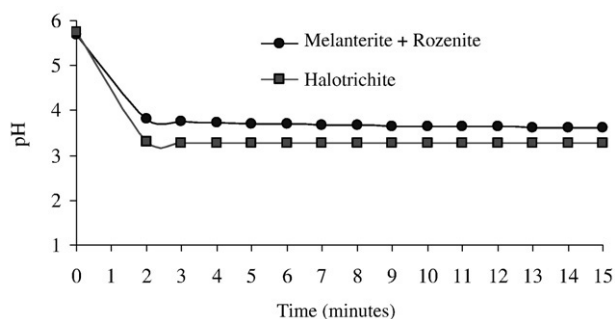
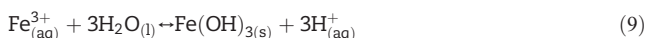
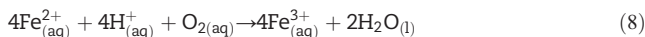
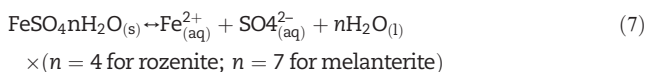
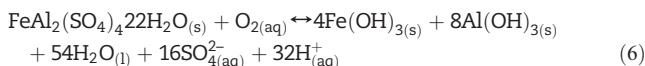


Fig. 10 – pH evolution during experimental dissolution of selected samples carrying Melanterite+Rozenite and Halotrichite, for a salt concentration of 20 g/L.

of hydrogen ions from hydrous sulphates, like it was observed in several AMD environments (e.g. Cravotta, 1994; Jambor et al., 2000).



Hydrolysis of trivalent ions, such as aluminium from halotrichite, provides more significant acidity to the solution.

In the case of Melanterite+Rozenite, oxidation of ferrous iron and subsequent hydrolysis and precipitation of ferric iron explain the observed pH fall. Fig. 11 presents the behaviour observed for the more common assemblage (Melanterite+Rozenite).

The relation between salt concentration and the resultant solution pH was analysed for 15 min (Fig. 11 a)). The best fit between these parameters (Fig. 11 b)) is very close to the equation obtained by Frau (2000) with pure melanterite, which demonstrates the reproducibility of the process for salt efflorescences carrying both hydrated sulphates.

Chemical analysis of the resultant solution reveals that, as expected, upon dissolution, iron and sulphate are the dominant constituents (Fig. 11 c)). However, other toxic elements are also released, providing indication that melanterite and rozenite are incorporating metals and arsenic via adsorption or coprecipitation.

These experiments demonstrate the role of the efflorescent mineralogy as transient storage of sulphate, acidity and metals. In that way, as the climatic seasonal cycles control the mineral stability, they have influence over the AMD properties and, therefore, they control its environmental impact.

In the event of rainfall, especially after prolonged dry periods, these highly soluble sulphates will dissolve and affect the properties of the receiving aquatic system. The environmental relevance of the rinse-out effect of efflorescent mineralogy in AMD systems is well documented (e.g. Nordstrom and Alpers, 1999). According to Frau (2000), the longer the dry period, the more intense the environmental impact during the subsequent wet period.

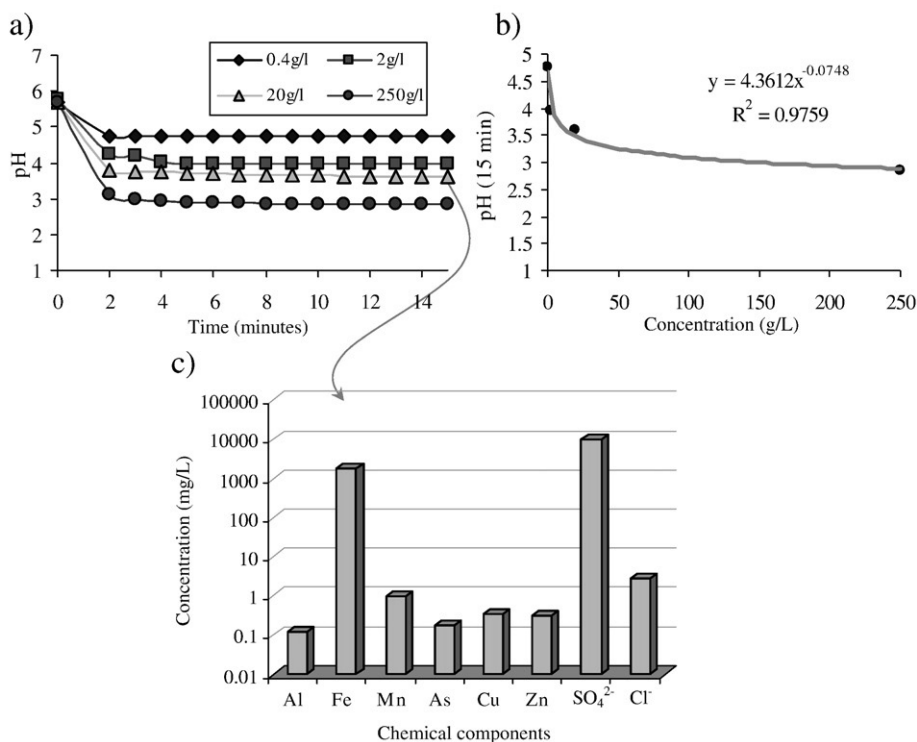


Fig. 11 – Results of experimental dissolution of Melanterite+Rozenite. a) pH behaviour for different salt concentrations; b) Correlation between pH and salt concentration; c) Chemical composition of the remnant solution upon dissolution (for the tested concentration of 20 g/L).

Figs. 10 and 11 show that iron and aluminium sulphates can be dissolved instantaneously, releasing pollutants into the water. Nevertheless, in field conditions, the relation between salts dissolution and aquatic contamination may be somewhat disguised by other factors such as dilution caused by rainfall. Consequently, a small rainy event may be of major concern, while that a strong and prolonged will assure dilution and therefore minimize the environmental risk.

4.2. Iron-rich ochre precipitates

Ochre precipitates of iron (III)-bearing minerals can be found at the waste-dumps and along the effluent channel. Fig. 12 exemplifies representative occurrences as:

- flocculated materials on the water–air interface (Fig. 12 a and b)),
- streambed coatings, that progress to encrusting as precipitation proceeds (Fig. 12 c)),
- iron-cements inside solid crusts (Fig. 12 d and e)).

Encrusting develops as secondary minerals are accumulated, in such a way that the most indurate crusts represent an advanced stage of ochre precipitation. They occur typically at the waste-dumps, and, convert over time to iron-rich hardpans, herein defined accordingly with Lottermoser and Ashley (2006). In such hardpans, the iron (III)-bearing minerals are the typical cements, acting as strong binding agents for mine wastes. Others, less solid or even loosely, modes of occurrence, are broadly distributed since they can be observed in the entire system, including at the confluence in the Coura River.

4.2.1. Mineralogy and morphology

Jarosite, schwertmannite and goethite are the main components of generally impure ochre precipitates. Ferrihydrite and lepidocrocite are rare and have restricted occurrences. The first was only observed in incipient and very fragile crusts that were collected after long lasting rainy periods. The second was identified inside very solid masses, in association with other supergene materials like sulphur and goethite, composing the cement of the most iron-rich hardpans.

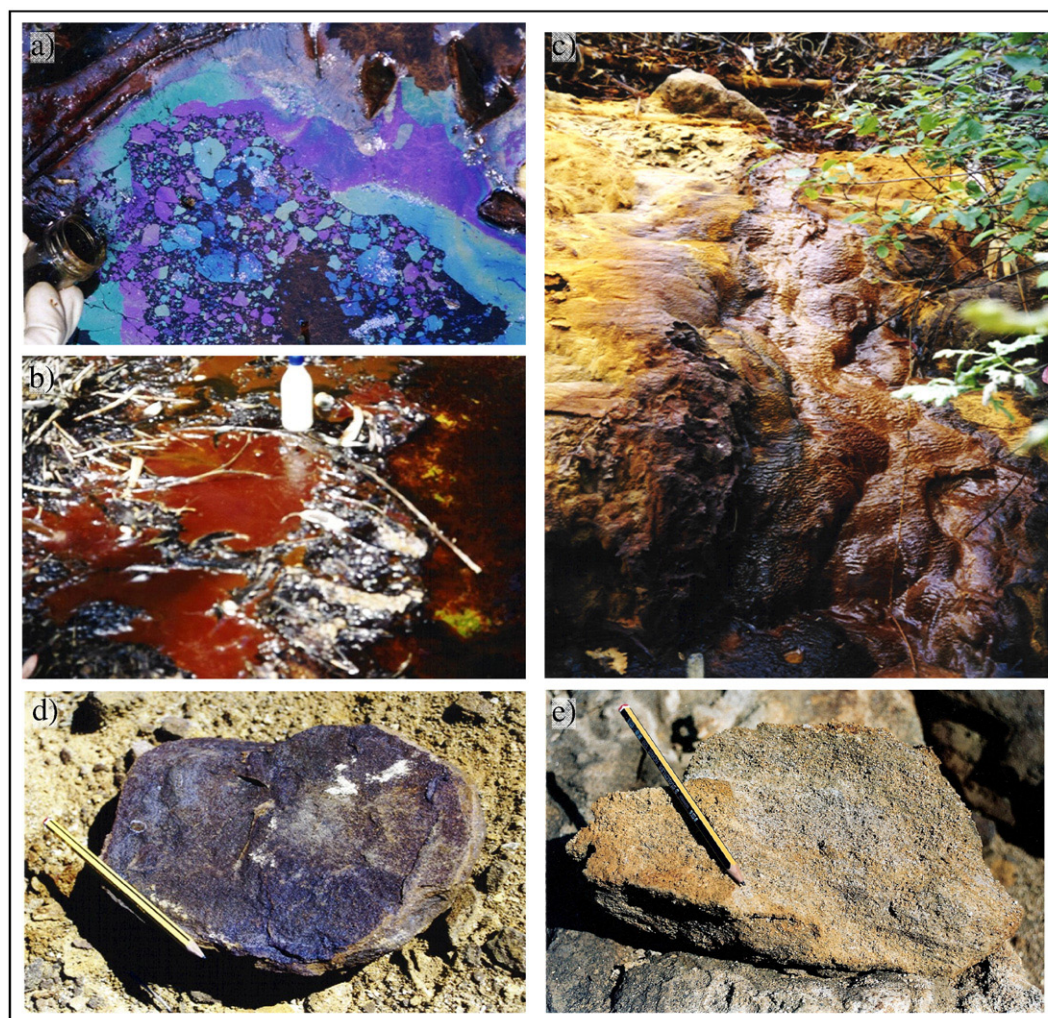


Fig. 12 – Field images of representative occurrences of ochre precipitates. a) water-floating brittle films displaying iridescence; b) Thick layers of orange sludge in the water–air interface; c) Encrusted coatings on the surfaces of the effluent channels; d, e) ochre-cements inside iron-rich hardpans.

From the more common minerals, the hydroxysulphate jarosite is the most crystalline. It is often identified as pure coatings at the most acidic seepages, where it gives a yellow colour to the exposed surfaces. It also forms mixtures with other minerals, principally schwertmannite, encrusting the effluent channels. Schwertmannite occurs mainly as brittle iridescent thin films and as light orange sludge. Both types of occurrences are fragile and consequently easily broken and dispersed in the water flow. During summer, in small remnant seeps and in slow flowing water, it is possible to observe several millimetres layers of bright orange sludge composed by pure schwertmannite. In those conditions its identification is rather simple because, although poorly crystalline, it has an unconfoundable diffraction pattern. Morphological features, observed in SEM-SE (Fig. 13), are diagnostic, especially valuable when schwertmannite occurs in complex mixtures. Fig. 13 c) shows tubular aggregates with typical specular and foam habits. These morphological aspects suggest that crystal growth take place as foam structures from thin and continuous iron rich films.

Goethite is generally poorly to moderately crystalline and presents spherical habit (Fig. 13b)). The most powdered aggregates are often enriched with sulphate. It occurs at the waste-dumps, but it is more abundant along the creek, where it forms light orange mixtures with schwertmannite. Pure goethite is more common at higher distances from waste-dumps, where it appears as orange to brown precipitates coating the rock surfaces.

The evidence of crystallinity, expressed by diffractometer analysis, decreases in the following order: Jarosite-Goethite-Schwertmannite.

4.2.2. Environmental relevance of ochre-precipitates distribution

The distribution of the ochre precipitates, encrusting stream-beds (Fig. 14, deserves the following comments:

- at the waste-dumps (ValdR, V1, V2 and V6) prevails jarosite; its content decreases along the creek as the distance relative to the waste-dumps increases, until it disappears at V7.
- At V7 occur the goethite-richer precipitates.
- Along the creek, between V3 and V9, the mixtures are composed by variable proportions of schwertmannite and goethite with minor jarosite;
- As distance to the waste-dumps increase there is a progressive importance of goethite relatively to schwertmannite.
- In the longest rainy periods the precipitates formed at the waste-dumps appear enriched in low crystallinity materials.

The distribution reported in Fig. 14 agrees with the paragenetic relations described by Bigham et al. (1996) for jarosite, schwertmannite and goethite. It is known that jarosite forms under more acidic conditions than the others (Baron and Palmer, 1996; Swayze et al., 2000), which explains

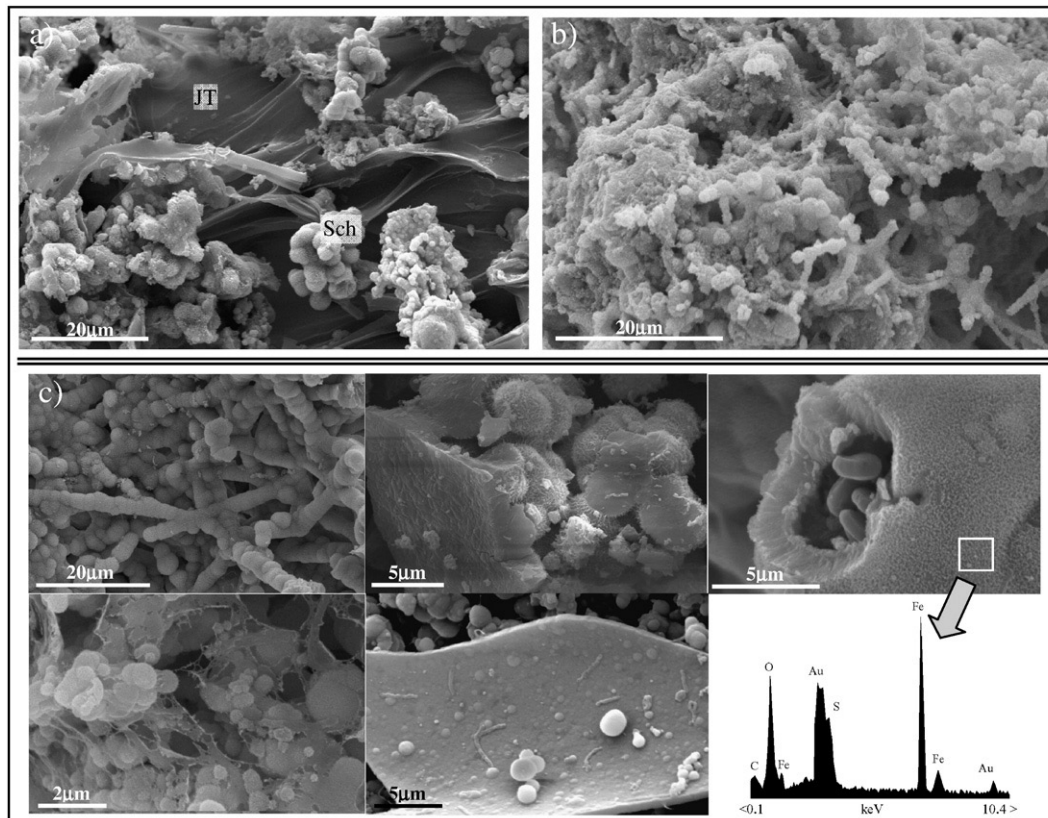
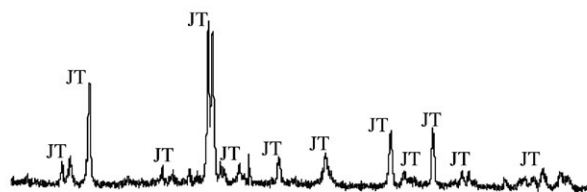


Fig. 13 – SEM-SE images showing morphological characteristics of the iron(III)-minerals that compose the ochre precipitates. a) sample with jarosite and schwertmannite collected at V4; b) sample composed of poorly crystalline goethite collected at V7; c) typical habits of schwertmannite and EDS spectrum of spherical schwertmannite.

SAMPLING SITE: ValdR
pH range [2.07,3.26]

DESCRIPTION:
yellow hard coatings

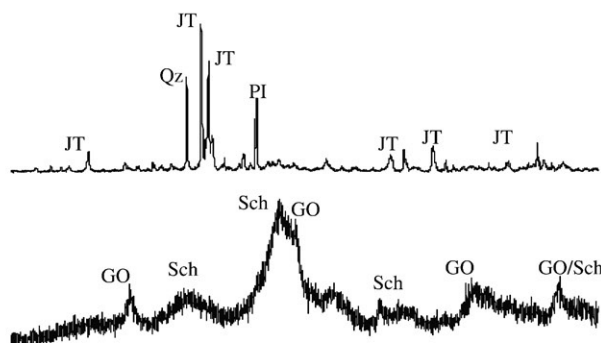
MINERALOGY: JT



SAMPLING SITES: V1, V2, V6
pH range [2.46,3.79]

DESCRIPTION:
- yellow-orange coatings forming hard layers;
- very fragile orange crusts (typically after long lasting rainy periods)

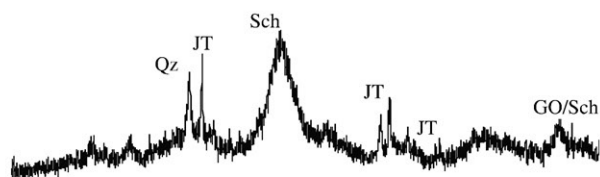
MINERALOGY: JT>(Sch+GO)



SAMPLING SITE: 05A
pH range [3.04,3.66]

DESCRIPTION:
Friable encrusted coatings with vesicular appearance; often incorporate living algae

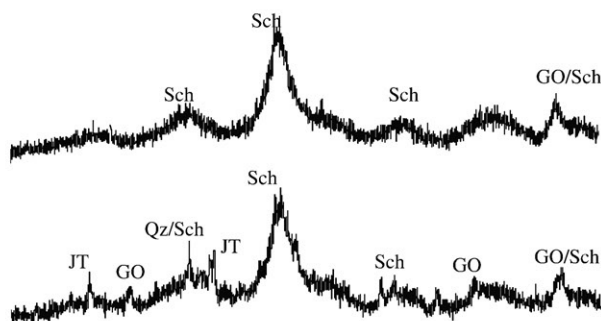
MINERALOGY: Sch > JT



SAMPLING SITES:
V3, V4, V5, V9
pH range [2.61,3.28]

DESCRIPTION:
Fragile to hard encrusted coatings with alternated ochre colours; often incorporate biological material (fossilized plants and wood)

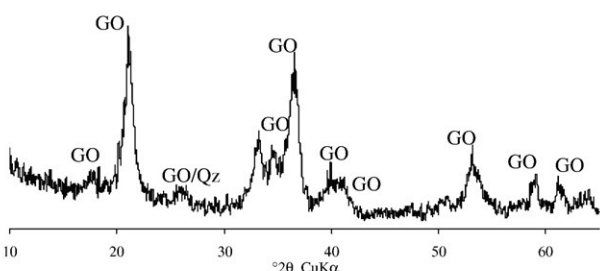
MINERALOGY: Sch > (GO+JT)



SAMPLING SITE: V7
pH range [2.7,3.73]

DESCRIPTION:
Thin orange-brown coatings over rock surfaces

MINERALOGY: GO>>Sch

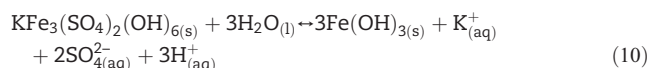


INCREASING DISTANCE TO THE WASTE-DUMPS

Fig. 14 – XRD patterns and description of the ochre precipitates from the encrusted effluent channels. JT – Jarosite; GO – Goethite; Sch – Schwertmannite; Qz – Quartz; PI – Pyrite. The pH range at each sampling site was extracted from Valente (2004) and Valente and Leal Gomes (2008).

its predominance at ValdR. Here, persistence of jarosite is insured by the constant supply of acidic effluent from the interior of the waste-dumps and also resulting from the dissolution of the soluble sulphates that were abundantly observed at this site.

Downstream, between V3 and V9, the effect of dilution induces an increase in the pH values, which promotes the instability of jarosite relatively to the oxyhydroxides. Eq. (10) gives the transformation reaction, which produce protons. Nevertheless, dilution remains the prevailing factor, inducing pH to rise.



In those less acidic conditions, jarosite can be replaced by schwertmannite. The same occurs at the waste-dumps (V1, V2 and V6) during the rainiest periods, which suggests the influence of seasonal variations in the minerals distribution.

At the upper section of the Poço Negro creek, the low crystallinity and the schwertmannite-rich compositions may be revealing an incipient stage in the paragenetic sequence. On the other hand, goethite represents a more advanced stage, since it forms at higher pH values and as a transformation product of less crystalline phases. In fact, it is known that over time schwertmannite may convert to goethite (Bigham et al., 1996; Bigham and Nordstrom, 2000). This will explain the downstream enrichment in goethite and its predominance at the more distant sampling site (V7).

These results indicate that XRD data on the ochre mixtures may give valuable information regarding the environmental conditions related with AMD. In that way, abundance of jarosite outside the waste-dumps may indicate a recent event of acidic contamination, which is, in general, due to erosion processes taken place at the waste-dumps. This was observed after episodic instability, promoted by strong rainfall events or by anthropogenic activities, such as the illegal practice of sports on the waste-dumps. In those conditions, the spreading of the jarosite halo is a response to higher contents of acidity and sulphate in the effluent, which is promoted by the chemical reactivation of sulphide-rich wastes. Progressively, dilution attenuates this effect and schwertmannite gains importance in the ochre mixtures. In fact, the presence of low crystallinity materials, such as the floating films of schwertmannite, marks the incipient effect of natural attenuation processes. Long lasting stability periods promote further evolution to goethite. As a result of the repetition of these processes, the channel is coated with encrusted layers that present alternated colour and composition.

5. Conclusion

The environmental minerals associated with AMD at Valdarcas occur as salt efflorescences or as ochre mixtures, both typically iron-dominant. The abundance, rather than the variety, of iron minerals is a consequence of the primordial composition of the mine wastes, since pyrrhotite and pyrite are the most abundant parent sulphides, leading to the generation of highly iron-rich solutions.

Regarding efflorescences, the majority are composed by gypsum and by the simple hydrated ferrous sulphates, rozenite and melanterite. Lesser amounts of Al-sulphates were also frequently detected. Salts of other transition metals were more rarely observed, which reflects the chemical potential of the iron-rich AMD from which they precipitate. The principal modes of occurrence, the composition of the mineral assemblages, as well as the geometry of the inter-growths, suggest that the distribution and paragenesis of soluble salts are controlled by the following main factors:

- climatic seasonal variation – determines the evaporation conditions and the water availability; consequently controls the succession of precipitation-dissolution cycles and the transformations allied to hydration and neutralization.
- topography and erosion – diversify the microclimate conditions that behave as thermodynamic microenvironments for precipitation at the waste-dumps.
- composition of AMD, mainly acidity and the activity of sulphate and metals – variations in composition, especially concerning the relation between iron and other metals, control the element fractionation, by diversifying the equilibrium conditions.
- hydrologic configuration of the superficial drainage – controls the fluxes of percolation, as well as the existence of seepages and ponded water, that by its turn influences the chemical composition and the oxidation conditions of AMD.

Laboratory experiments with efflorescences carrying iron and aluminium sulphates have demonstrated the ability to produce acidic, metal and sulphate rich solutions. In that way, these experiments close simulate the influence that these type of environmental minerals exercise over the quality of the nearby aquatic system. Such influence is especially important during rainfall events, after dry periods, since dissolution may promote peaks of acidic contamination, related with AMD emanating from the waste-dumps.

Ochre precipitates were the other relevant environmental minerals identified at Valdarcas. They refer to iron (III)-bearing minerals that include jarosite, schwertmannite and goethite and more rarely ferrihydrite and lepidocrocite. These minerals occur with variable proportions in the ochre mixtures that are disseminated in the waste-dumps and downstream, in the riverine system. The relative mineral proportions, in concert with the crystallinity of the mixtures, is rather variable downstream and over time, accordingly with the AMD conditions. For instance, the detection of well crystalline precipitates, enriched in jarosite, at lower sections of the creek, indicates the occurrence of recent contaminant events, generally related with erosion processes at the waste-dumps.

During the year of 2007, engineering rehabilitation works were conducted at the waste-dumps, in order to homogenize the surface and to implement measures for erosion control. In the beginning of 2008 the waste-dumps, which have been covered with soil, were also seeded and planted with autochthon vegetation. Future impact of this rehabilitation project should be, from now on, subject to monitoring. For that purpose, mineralogical composition and spatial

distribution of ochre precipitates along the Poço Negro creek can be proposed as expeditious mineralogical indicators, which enhance the relevance of these AMD-precipitates as environmental minerals.

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