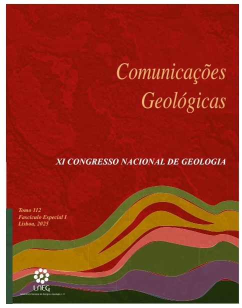
LNEG Laboratório Nacional de Energia e Geologia, I. P.

Comunicações Geológicas

Comunicações Geológicas (2025) 112, Especial I, 217-220
ISSN: 0873-948X; **e-ISSN**: 1647-581X

Potential accumulation of strategic elements in mining dams - from remining to rehabilitation

Acumulação potencial de elementos estratégicos em barragens mineiras – da remineração à reabilitação



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DOI: https://doi.org/10.34637/dtz1-d457
Recebido em 27/09/2023 / Aceite em 12/04/2024
Publicado online em abril de 2025

Artigo original
Original article

Abstract: Raw materials, from oil to industrial minerals, are essential to the efficient functioning of the world economy. However, the extraction of base metals, for example, allowed the mobilization and accumulation of large amounts of reactive wastes, triggering critical environmental problems. The Iberian Pyrite Belt, one of the largest metallogenetic provinces in the world, is an example of this, as it presents numerous abandoned mining exploitations that were closed without or with inadequate environmental remediation. However, Europe is particularly vulnerable, as it depends on importing these metals. In this context, the present study addresses the theme of remining, assuming premises of rehabilitation and circular economy. The work focused on one of the most Portuguese paradigmatic mining complexes - the São Domingos mine. The methodological protocol was based on drilling to characterize stream sediments. The results revealed an estimate of the economic potential of accumulated sediments, offering a hopeful and optimistic outlook. These suggest reusing critical elements, such as Ag and Sc. The information in this research aims to help the competent authorities build a recovery strategy based on the valorization of resources centered on the circular economy.

Keywords: mining sediments, drilling, remining, rehabilitation, circular economy.

Resumo: As matérias-primas, desde o petróleo aos minerais industriais, apresentam-se como essenciais ao funcionamento eficiente da economia mundial. Contudo, a extração de metais básicos, por exemplo, permitiu a mobilização e acumulação de grandes quantidades de rejeitos reativos, desencadeando sérios problemas ambientais. A Faixa Piritosa Ibérica, uma das maiores províncias metalogenéticas do mundo, é exemplo disso, pois apresenta inúmeras antigas explorações mineiras abandonadas, que foram encerradas sem ou com inadequada remediação ambiental. No entanto, a Europa está numa posição particularmente vulnerável, pois encontra-se dependente da importação desses metais. É neste contexto que o presente estudo aborda a temática da remineração, assumindo premissas de reabilitação e economia circular. O trabalho incidiu sobre um dos complexos mineiros portugueses mais paradigmáticos - a mina de São Domingos. O protocolo metodológico baseou-se na caracterização de sedimentos fluviais, através de sondagens. Os resultados revelaram uma estimativa do potencial económico dos sedimentos acumulados. Estes sugerem a possibilidade de reaproveitamento de elementos críticos, como a Ag e o Sc. As informações contidas nesta investigação visam auxiliar as autoridades competentes a construir uma estratégia de recuperação baseada na valorização de recursos, assente na economia circular.

Palavras-chave: sedimentos mineiros, sondagens, remineração, reabilitação, economia circular.

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1. Introduction

Raw materials, from oil to industrial minerals, are essential to the efficient functioning of the world economy. Although extractive activity boosts the economy and creates wealth, it presents serious conflicts of interest with other territory uses (e.g., Gomes et al., 2013). The previous extraction of metals triggered, all over the world, the mobilization and accumulation of large quantities of reactive waste, causing environmental problems in terms of soil, water, and vegetation (e.g., Valente et al., 2012). An example is the Iberian Pyrite Belt, which has numerous old mining operations, closed and abandoned with no or weak environmental protection, ultimately promoting a slowdown in resource extraction (e.g., Gomes, 2021). However, Europe is currently in a period of growing demand for raw materials driven by emerging technologies and economies. Therefore, there is a need to supply high-tech metals, essential ingredients in the incorporation and development of technologically sophisticated products, often called "environmentally friendly" (e.g., lithium batteries, solar panels), and even equipment related to medicine, which contribute to an improvement in quality of life. Metallic elements, such as Cu, Zn, and Sc, included in this category of importance, are also essential for maintaining the development levels of current societies. In this sense, the introduction of the concepts of mining waste reuse and recycling must be able to reduce the consumption of natural resources, limit the production of waste, create an economy, stimulate research and local industries, create jobs, and mainly create a change in the environmental paradigm (Lottermoser, 2010). In the context of remining, the circular economy ultimately reconciles the concepts of environmental protection and resource extraction.

The present study is inserted into this paradigm, addressing the possibility of remining, from a perspective of environmental rehabilitation and a circular economy.

2. Study Area

The study focused on one of the most paradigmatic Portuguese mining complexes – the São Domingos mine in the Iberian Pyrite Belt (Figura 1a).

Mobilizing more than 20 Mt of materials, fresh and acid water reservoirs, and land sterilized by metallurgical processing dictated the radical alteration of 296 ha of the 6000 ha comprising the enterprise (Guita, 2011). The exploitation ended and was abandoned in the 1960s. Waste of disparate materials, such as sulfides, gossan, slag, ash, iron oxides, sterile rock, sludge, and debris, accumulated for years in waste

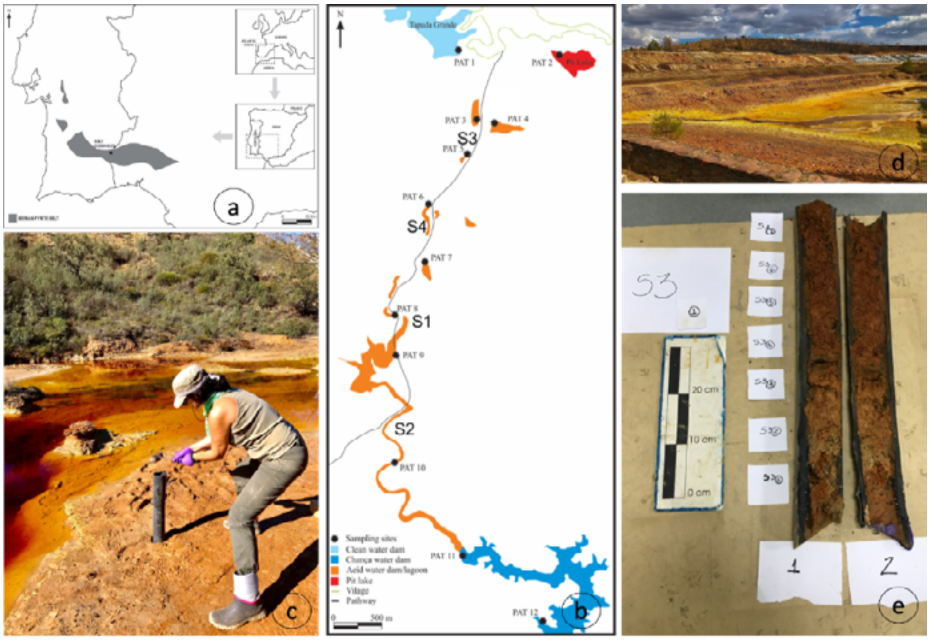

Figura 1. a) Location map; b) respective drillings along the river system (S1; S2; S3; S4); c) Sampling of accumulated sediments; d) Example of one of the sampled dams (S3); e) Preparation of drill material for different analyses. (PATs = different dams along the watercourse)

Figura 1. a) Mapa de localização; b) respetivas sondagens ao longo do sistema fluvial (S1; S2; S3; S4) ; c) Amostragem de sedimentos acumulados; d) Exemplo de uma das barragens amostradas (S3); e) Preparação do material para as diferentes análises. (PATs = diferentes barragens ao longo do curso de água)

dumps over 14 m high (Cordeiro *et al.*, 2017).

FPI has relevant potential in high-technology or critical supply metals (*e.g.*, In and Ge). Regarding the mining area of São Domingos, despite having never been explored, prospecting and research contracts for the waste dumps suggest potential for Au and Ag (www.edm.pt).

The region's climate is considered dry sub-humid (Gomes, 2021). According to the same author, climate data also revealed that in recent years, precipitation has been considerably reduced and temperature has increased, with the least rainy period being 2016/17 (203 mm), corresponding to the sampling period.

3. Materials and Methods

The methodological protocol was based on the characterization of sediments obtained from four surveys carried out at the end of 2016. These were implemented in dams that suffered clogging phenomena and the water lines that drain the entire mining area (São Domingos and Mosteirão stream) (Figura 1b, c, d). The laboratory procedures included X-ray diffraction (XRD) in different fractions: < 2 mm and < 2 µm. A Philips PW1710 diffractometer was used to obtain the diffractograms, with CuKα radiation, voltage of 40 kV, and intensity of 20 mA. To study the first fraction, it was passed through a mesh sieve < 2 mm. After this phase, the powder was obtained in an agate mill, followed by XRD analysis with a sweep in the angular range 3º to 65º 2θ. The identification and semi-quantification of the phases present were based on the diagnostic peaks described in Brindley and Brown (1980).

The < 2 µm fraction identification was carried out on oriented blades air-dried and with the application of chemical treatments (sample saturated with ethylene glycol) and thermal treatments (sample subjected to heating at 490ºC), according to the method used in the clay laboratory of the DCT/UM, including routine washing, centrifugation, siphoning and decantation operations (Lima, 2004). As it is the one that contains the most intense reflections of clay minerals and associated minerals, the diffractograms were obtained with scanning in the angular range of 2 to 35º 2θ (Brindley, 1980). For each sample, three diffractograms were taken corresponding to three different laboratory conditions, which helps diagnose the mineralogical phases present.

Samples from the same two fractions were also subjected to chemical analysis (every 20 cm). These were obtained after grinding by induced plasma source mass spectrometry (ICP/MS) and digestion with

Table 1. Average concentrations of selected elements in each drilling (S1 to S4) and estimated volumes. *S1 (n=6); S2 (n=7); S3 (n=6); S4 (n=9).

Tabela 1. Teores médios de elementos selecionados em cada sondagem (S1 a S4) e estimativa de volumes. * S1 (n=6); S2 (n=7); S3 (n=6); S4 (n=9).

	Drills	S1	S2	S3	S4
Average* (< 2 mm)	Dam area (m2)	17145	11081	3526	4860
	Depth (m)	1.0	1.3	1.0	1.8
	Volume (m3)	17145	14405	3526	8748
	Cu (mg/kg)	709	182	250	184
	Zn (mg/kg)	318	131	110	117
	As (mg/kg)	2507	5612	536	519
	Au (mg/kg)	144	62.3	83.0	62.0
	Ti (%)	0.36	0.44	0.46	0.51
	Ag (mg/kg)	6.22	3.01	2.47	1.91
	Sb (mg/kg)	656	369	83.6	42.4
	∑(REE) (µg /kg)	114	150	193	204
	Sc (µg/kg)	144	62.3	83.0	62.0
	Co (mg/kg)	11.8	1.14	2.17	5.89
	Mg (%)	0.26	0.22	0.24	0.32

Table 2. Correlation matrix between survey elements selected for their potential economic interest.

Tabela 2. Matriz de correlação entre elementos das sondagens, selecionados pelo potencial interesse económico.

	Cu	Zn	As	Au	Ti	Ag	Sb	Sc	Co	Mg
Cu	1.000									
Zn	0.979	1.000								
As	-0.006	0.143	1.000							
Au	0.991	0.946	-0.066	1.000						
Ti	-0.887	-0.897	-0.393	-0.883	1.000					
Ag	0.964	0.982	0.258	0.942	-0.964	1.000				
Sb	0.827	0.898	0.556	0.782	-0.950	0.945	1.000			
Sc	0.991	0.946	-0.066	1.000	-0.883	0.942	0.782	1.000		
Co	0.885	0.889	-0.229	0.842	-0.601	0.788	0.619	0.842	1.000	
Mg	-0.037	-0.032	-0.656	-0.086	0.470	-0.221	-0.376	-0.086	0.422	1.000

aqua regia (Actlabs, Canada).

4. Results and Discussion

The results revealed the accumulation, at different depths, of chemical elements of high economic interest (Table 1) despite the levels being low when compared to waste from mud dams in the active mining industry (Lemos *et al.*, 2020). However, it should be noted that these are samples of material that have undergone transport and, therefore, dilution. These values may be higher in waste dumps and piles of washed ore. There are currently prospecting and exploration contracts for waste sites, with potential for Au and Ag, in the region under study. Therefore, the aim here is to assess the most pessimistic scenario. Even so, the levels of Ag and Sc stand out when compared with levels reported for primary deposits (Rämä *et al.*, 2018). Table 2 presents the correlation between the elements, showing a strong relationship between Ag and some metals. The mineralogical analysis, supported by the literature (Rämä *et al.*, 2018), suggests that jarosite may be a potential source of Ag (besides sulfides, namely pyrrhotite). So, in the sense of reuse, the concentration of Ag+Cu+Zn+Au+Sb+Sc can be increased and, to a lesser extent, Co. The remaining elements have a low relationship with these metals.

Table 3. Average abundance (%) of minerals identified by XRD and estimate of a global density for the drilling area. Q=quartz; F=feldspar; P=plagioclase; Mi=mica; CM=clay minerals; Pyr= pyrrhotite; Go=goethite; Jt = jarosite; Si = siderite. A.N.=normalized abundance.

Tabela 3. Abundância (%) média dos minerais identificados por DRX e estimativa de uma densidade global para a área das sondagens. Q=quartzo; F=feldspato; P=plagioclase; Mi=mica; CM=minerais de argila; Pyr= pirrotite; Go=goethite; Jt = jarosite; Si = siderite. A.N.=abundância normalizada.

Drills	Q	F	P	Mi	Cm	Pyr	Go	Jt	Si
S1	26.2	3.9	19.9	9.1	11.9	4.9	5.6	21.6	18.5
S2	30.4	3.7	31.9	9.9	6.7	2.5	1.9	18	
S3	49.6	7.7	17.1	6.5	5.9	1	5.5	13.1	
S4	42.9	8.7	19.2	9.7	6.9		2.7	12.8	
S5	52.8	5.8	9.2	7.8	9.6		6.2	12.8	
Average	40.4	6	19.5	8.6	8.2	2.8	4.4	15.6	18.5
A.N. (%)	32.6	4.8	15.7	6.9	6.6	2,.3	3.5	12.6	14.9
Density	2.65	2.76	2.76	3	2.68	4.53	5	3.5	3.9

Global density (of all drills) - 3,12

Considering the dominant mineralogy (Table 3), it is possible to estimate a theoretical global density of accumulated materials of around 3.1 and thus calculate the tonnage. With these data, the feed contents of a possible recovery system for each element are obtained (Table 4).

A possible recovery potential simulation (Table 5), considering typical recovery rates from jarosite and pyrrhotite, suggests that Ag becomes attractive and comparable with primary ores (Rämä *et al.*, 2018). The same can be seen in relation to Sc, comparing with values indicated by Yagmurlu *et al.* (2016) and Binnemans *et al.* (2015) (126 mg/kg and 1.2 mg/kg) for recovery of Sc from bauxite waste. The theoretical recovery values for these metals are based on a bibliographic survey and aim to demonstrate the potential for reuse (Falagán *et al.*, 2017; Araya *et al.*, 2020; Wang *et al.*, 2020). However, it should be noted that the added value will be more expensive due to the need for pre-treatments at the metallurgy level.

This assessment, therefore, suggests that the economic viability of remining some of the chemical elements present in the sediments accumulated in mining dams be considered, like what is starting to happen in other parts of the world. Therefore, the supply of natural resources from the subsoil invariably depends on the energy available to extract them. In other words, the problem is not just the amount of mineral resources in the Earth's crust but the energy required to obtain them from geological materials.

5. Final Considerations

The increasing development of technologies in metallurgy, fueled by

Table 4. Feed contents of each element in the entire area subject to drilling. All elements are expressed in mg/kg, except REE (µg/kg).

Tabela 4. Teores de alimentação de cada elemento na globalidade da área sujeita a sondagem. Todos os elementos estão expressos em mg/kg, com a exceção dos REE (µg/kg).

	Cu	Zn	As	Au	Ag	Sb	∑(REE)	Sc	Co
Concentration	385	195	2903	94	4	384	146	94	6

Tabela 5. Simulação de potencial de recuperação a partir da jarosite e da pirrotite. Todos os elementos estão expressos em mg/kg, com a exceção do Au (µg/kg).

Table 5. Simulation of recovery potential from jarosite and pyrrhotite. All elements are expressed in mg/kg, except Au (µg/kg).

Mineral	**Jarosite**						
Abundância no concentrado	10 %						
Elemento	Cu	Zn	Au	Ag	Sb	Sc	Co
Recuperação	80%	80%	40%	40%	80%	80%	80%
Teor no concentrado recuperado	3080	1559	375	16	3072	749	50
Mineral	**Pirrotite**						
Abundância no concentrado	2 %						
Elemento	Cu	Zn	Au	Ag	Sb	Sc	Co
Recuperação	80%	80%	40 %	40 %	80 %	80 %	80 %
Teor no concentrado recuperado	15398	7797	1873	78	15358	3746	248

the need to recover increasingly lower levels, meets the demands of the circular economy, enabling the recovery of mining waste.

In this sense, associated with the sustainability theme, the circular economy paradigm is applied to waste recovery in São Domingos.

The simulation presented for the sediments accumulated in this water system, in such a pessimistic scenario as shallow dams, still suggests a potential appreciation through the recovery of metals, such as Ag and Sc.

Therefore, there is an interest in evaluating in greater detail other potential targets in priority areas of the mining complex, namely the large accumulations of fine waste in the industrial area of Achada do Gamo.

Therefore, priority research areas include re-evaluating potential targets, investment in cutting-edge technology, and, fundamentally, ensuring passive sustainable management of the coexistence of the binomial environment and economy.

Acknowledgments

National funds finance this work through FCT - Fundação para a Ciência e a Tecnologia, I.P., within the scope of projects Refªs UIDB/04683/2020 and UIDP/04683/2020. Patrícia Gomes thanks FCT for the research grant under POCH, supported by the European Social Fund and MCTES National Funds, with the reference SFRH/BD/108887/2015.

References

Araya, N., Kraslawski, A., Cisternas, L.A., 2020. Towards mine tailings valorization: Recovery of critical materials from Chilean mine tailings. *Journal of Cleaner Production*, **263**: 121555. https://doi.org/10.1016/j.jclepro.2020.121555.

Binnemans, K., Pontikes, Y., Jones, P.T., Gerven, T., Blanpain, B., 2013. Recovery of rare earths from industrial waste residues: a concise review. *Journal of Cleaner Production*, **99**: 17-38.

Brindley, G.W., 1980. Order-disorder in clay mineral structures. In G. W. Brindley e G. Brown, Eds., *Crystal Structures of Clay Minerals and their X-ray Identification, Mineralogical Society*, London, 125-195.

Brindley, G.W., Brown, G., 1980. *Crystal Structure of Clay Minerals and Their X-ray Identification*. The Mineralogical Society, London.

Cordeiro, M., Valente, T., Grande, J.A., Gomes, P., 2017. *Mapping mining wastes and analyzing affected areas through expeditious physico-chemical parameters.* XII Congreso Nacional de Geoquímica/XI Congreso Ibérico de Geoquímica, Linares, 26 a 28 de Setembro, 178-183.

EDM - Empresa de desenvolvimento mineiro, S.A. (www.edm.pt)

Falagán, C., Grail, B.M., Barrie Johnson, D., 2017. New approaches for extracting and recovering metals from mine tailings. *Minerals Engineering*, **106**: 71-78, https://doi.org/10.1016/j.mineng.2016.10.008.

Guita, R.J., 2011. *A Mina de São Domingos (Mértola, Baixo Alentejo, Portugal): actividade industrial moderna (1854-1966)*. Ciclo de Encontros de Historiados Locais “Áreas industriais e comunidades operárias”, Instituto de História Contemporânea, Portimão.

Gomes, P., Valente, T., Pamplona, J., Sequeira Braga, M.A., Pissarra, J., Grande J. A., 2013. Metal uptake by native plants and revegetation potential of mining sulfide-rich waste-dumps. *Journal of Phytoremediation*, **16**: 1087–1103. https://doi.org/10.1080/15226514.2013.810586

Gomes, P., Valente, T., Pereira, P., 2018. Addressing quality and usability of surface water bodies in a Mediterranean semi-arid region. *Environmental Processes*. https://doi.org/10.1007/s40710-018-0329-0.

Gomes, P., 2021. *Impact of acid mine drainage on the environmental quality and potential accumulation of strategic metals in water dams located in the Iberian Pyrite Belt*. PhD thesis, Univ. Minho, Braga.

Lemos, M., Valente, T., Reis, P.M., Fonseca, R., Delbem, I., Ventura, J., Magalhães, M., 2020. Mineralogical and Geochemical Characterization of Gold Mining Tailings and Their Potential to Generate Acid Mine Drainage (Minas Gerais, Brazil). *Minerals*, **11**: 39. https://doi.org/10.3390/min11010039.

Lima, A.S., 2004. *Hidrogeologia de Regiões Graníticas (Braga – NW Portugal)*, Universidade do Minho, Tese de Mestrado.

Lottermoser, B., 2010. *Mine wastes – characterization, treatment and environmental impacts*. Springer, 3rd edition, Berlin.

Rämä, M., Nurmi, S., Jokilaakso, A., Klemettinen, L., Taskinen, P., Salminen, J., 2018. *Thermal Processing of Jarosite Leach Residue for a Safe Disposable Slag and Valuable Metals Recovery*. Metals, **8**: 744. https://doi.org/10.3390/met8100744.

Valente, T., Gomes, P., Pamplona, J., de la Torre, M.L., 2012. Natural stabilization of mine waste-dumps - Evolution of the vegetation cover in distinctive geochemical and mineralogical environments. *Journal of Geochemical Exploration*, **123**: 152–161. https://doi.org/10.1016/j.gexplo.2012.05.005.

Wang, Y., Yang, H., Zhang, G., Kang, J., Wang, C., 2020. Comprehensive recovery and recycle of jarosite residues from zinc hydrometallurgy. *Chemical Engineering Journal Advances*, **3**: 100023. https://doi.org/10.1016/j.ceja.2020.100023.

Yagmurlu, B., Dittrich, C., Friedrich, B., 2016. Recovery of scandium from bauxite residue by selective precipitaton from leach solutions. *ALTA 2016 Uranium-REE Conference: 12th Annual Uranium Event, Australia*.