Deliverable code: EITRM109301

Deliverable number: D3.2

Deliverable name: A report with techniques for evaluation of CRMs variability

Deliverable description: Under the supervision of UNIBO, a review of all techniques, tools and methods for characterization of stockpiles, with regard to evaluation of CRMs variability, has been made.

Related Task: T3.2

Deliverable realized by: University of Bologna (UNIBO): F. Tinti, S. Kasmaeeyazdi

With the collaboration of: Bureau de Recherches Géologiques et Minières (BRGM), National Technical University of Athens (NTUA) and ORANO Mining

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INCO-Piles Deliverable

D3.2 Report with techniques for evaluation of CRMs variability

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Revision history

Date	Revised material	Revised by
16/09/2020	First draft version – presented at WP3 meeting	Sara Kasmaee (UNIBO)
13/11/2020	Second draft version	Francesco Tinti (UNIBO)
20/11/2020	Revised draft by Orano	Joachim Schick (ORANO)
27/11/2020	Third semi-final version	Sara Kasmaee (UNIBO)

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Contents

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1) Introduction

Task 3.2 of WP3 consisted of reviewing characterization techniques for understanding presence of raw materials (with special reference to critical raw materials - CRMs) inside the mining wastes (both stockpiles and tailings). The review covers different aspects, such as EU legislation in mining wastes management, environmental characterization of historical mining areas for pollution detection, grade characterization for recovery of valuable metals, innovative ways and approaches to understand the presence and value of CRMs within the entire mine life cycle. The present Deliverable 3.2 concludes with comments on the current standards and suggestions about a more effective characterization for practical and economic recovery of CRMs from stockpiles and tailings.

2) Background

Mining wastes and their managements are important subjects in many different aspects. The quantity estimation of waste within the European Union is based on four categories (ferrous metals, non-ferrous metals, industrial minerals, and coal). Over European Union, there are more than 4.7 billion tons of mining waste and 1.2 billion tons of tailings waste, which are stored historically. In each mining step, it is liable to generate mining waste with different physical and chemical properties. Their respective volumes, especially for access to the ore deposit, depend on the type of mining method and the type of the raw material. Similarly, their chemical composition depends on the type of ore, its geological setting, and its processing. For example, if two copper ores have respective contents of 7.0% and 0.7%, for one ton of produced copper, the first one will produce 11.5 tons of waste while the second will produce 164.4 tons of them (**Charbonnier, 2001**). Hence, waste characterization is an important part of efficient mine site management and traditionally, characterization of mining wastes is the study of the environmental impacts of mining, processing and storage of residuals (**EC, 2019**). Due to the environmental considerations, wastes can be divided base on their impacts on the surrounded area by (**EESI, 2020**):

- Acid & metalliferous drainage (AMD);
- Saline and/or sodic drainage (i.e. neutral mine drainage);
- Leaching and mobilisation of metals and toxic compounds.

Besides the progressive environmental rehabilitation, an essential supplementary step can be the inclusion of the recovery of raw materials from potential mining wastes.

The mining wastes are divided between extraction wastes (stockpiles) and processing wastes (tailings) – main distinctive properties are reported in **Table 1** (**Lemière et al., 2015**):

*Table 1. Main distinctive properties of stockpiles and tailings (***Lemière et al., 2015***)*

	Extraction wastes - stockpiles	**Processing wastes – tailings**
Material type	Coarse material abundant, large heterogeneity, before processing	Most fine-grained, sandy or silty, homogeneous, especially after crushing and grinding
Ore concentration	Ore elements in variable amounts	Valorised elements depleted; unused elements concentrated
Disposal type	Mechanically dumped	Slurry decantation, after processing, tailings are filtered to decrease water content before storage (applied from both ORANO and MYTILINEOS processing plants)

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2.1 Main characteristics of stockpiles:

There are different types of stockpiles due to their characterization, volume and PSD (Particle Size Distribution), the mining excavation method, processing production, etc. Hence, stockpiles have the following characteristics:

- stockpiles are formed by dumping excavated material from the mine, where characterization and analyses were made;
- stockpiles are divided between high or low-grade material, with distinction made on the basis of the target of processing plant feed;
- while high-grade stockpiles are generally entirely sent to the processing, low-grade stockpiles can be abandoned after mine closure, if no economic value was found;
- in the processing scheme, stockpiles are located between the mine and the processing plant;
- low-grade stockpiles can be formed by overburden, barren host rocks and low-grade mineralised rocks;
- abandoned low-grade stockpiles can have the same metals concentration of the mining area from which they were excavated, if not reagent with the environment is present;
- Blocks entering the stockpile are mixed homogeneously, so the characteristics of the material removed from the stockpile must be treated as variables;
- waste rocks in stockpiles are associated with mining ore for precious and base metals, coal, mineral sands and certain gems. They are often associated with sulphide minerals (such as pyrite), consisting of components of sulphur and metals such as arsenic, copper, lead, selenium etc. Most sulphide minerals when dug up and exposed to the environment (oxygen, air temperature and humidity levels), can oxidise and degrade to produce sulphuric acid and dissolved metals;
- the main consequence of degradation includes changes in material properties, therefore in these cases long term and abandoned stockpiles do not contain the same minerals of original characterization during the mine planning;
- abandoned low-grade stockpiles can cause environmental hazards, while on the other side can become economically profitable for metals recovery due to cut-off variations with respect to the time of original mines;

Figure 1 presents an example of low-grade abandoned stockpile (**Porcelli, 2006**)

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Figure 1. Abandoned low grade bauxite stockpile from a closed mining site in Apulia (Italy)

2.2 Main characteristics of tailings

Mining tailings have the following characteristics:

- tailings are composed by the residuals after treatment in the processing plant;
- characterization of tailings is generally made at the exit of the processing plant;
- metals concentration of tailings differs from the original concentration of the mine, since the target metals were separated in the processing plant;
- residual metals are always present in tailings because of different reasons:
    - technical (no specific processing is present for metals other than the target);
    - economic (no economic value of separating metals others than the target);
    - technical-probabilistic (not all target metals are separated in the processing plant).
- tailings may be disposed as a composite slurry or have sands and fines disposed separately; recently, filtration is performed at the end of the process to reduce water content~~;~~
- tailings can be a source of environmental hazard, since they have been treated as wastes by mining operators.

Figure 2 presents a case of tailings with evident hazard, which caused an environmental disaster (**Ádám et a., 2011**).

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Figure 2. Broken bauxite tailing dam causing spill and pollution spread in Hungary

2.3 Issues to be taken under control in both stockpiles and tailings

There are some issues, which should be considered for any action on stockpiles and tailings (**EESI, 2020**). They are:

- the potential for an adverse (acid, toxicant, salt, sodic, sediment) effect on the environment now or in the future, together with the containment and revegetation measures;
- the possibility for presence of reactive/dispersive clays inside the ore;
- the possibility for presence of other metals inside the ore.

2.4 Characterisation methods for mining wastes

Normally, there are different types of methods, which should be considered as the standard steps of mining wastes characterization, such as (**EESI, 2020**):

- **Field methods**
  - site screening, mapping large areas;
  - lab sample selection optimisation.
- **Site methods**
  - geological investigations;
  - geophysical measurements and studies;
  - geochemistry analysis: the behaviour of mine waste landforms – specifically out-of-pit waste rock dumps and tailings dams – is constantly evolving. The impact of waste geochemistry must be considered, as it affects environmental performance during operation, landform stability, and final rehabilitation and relinquishment;
  - groundwater monitoring: tailings storages, treatment ponds, waste rock stockpiles and stormwater runoff ponds, no matter how well constructed, will leak. If they contain or could solubilise toxicants,

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groundwater monitoring should be undertaken, since it is the most efficient way of measuring an environmental incident in progress;
- Remote sensing, airborne measurements.

2.5 From environmental characterization to economic resources characterization

Mine wastes may not only pose an environmental risk, but may also represent potential sources of valuable minerals and metals. Moreover, economic potential can be attributed much more to the historic mine waste products than current, and especially to those originating from ore extraction, because modern extraction technologies are more efficient compared to earlier technologies (**Tiess, 2010**, **Blengini et al., 2017**). On the other hand, not much is known about the characteristics of old and abandoned stockpiles and tailings. Exploration of the mine waste dumps can be done through intense sampling campaigns, in order to obtain a detailed spatial distribution of potentially valuable elements remained within wastes. In general, there are difficulties in sampling of mining wastes because of high heterogeneity of materials, large PSD in the case of stockpiles, high cost of sampling, huge wastes size and consequent difficulties to access all parts of mining wastes. Therefore, in the case of historical and abandoned sites, sampling from mining wastes can be accompanied by other types of direct and indirect analyses, already widely used for environmental detection, such as geochemistry, groundwater monitoring and remote sensing. A comprehensive study of mining wastes (specifically abandoned sites) can help not only to have a prospective vision for all kind of environmental issues and hazards, but also to have a resourceful consideration for raw materials demand trends, which can be well supported from these abandoned sites. The main point for management and characterization of mining wastes is that, due to the background, mining and piling procedures, each mine waste has its own properties and must be treated distinctively. Additional advanced methods, such as drone born techniques and remote sensing analysis can be used to monitor vast areas of mining wastes and detect any stability changes in time. These techniques can be transferred from environmental surveys to the raw materials' potential explorations within the mining wastes.

For better understanding of the available techniques, in the next section, documented case studies of stockpiles and tailings characterization for both environmental and resources recovery are presented.

Due to the wide range of applications and methods, the bibliography is divided into five methods including different case studies. At the end of each method presentation, there are references relating to the selected case studies and the classification of them due to the adopted parameters for INCO-Piles 2020.

Due to INCO-Piles 2020 Project objectives, each application presented is classified according to parameters presented in **Table 2**:

Table 2. Classification of presented case-studies

Residue type	Stockpile	Tailing
Mineral type	Metal	Non-metal
Characterization type	Grade	Environment
Use of remote sensing	Yes	No
Case study origin	RIS (MED-ESEE)	RREM
	Other European	Other non-European

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Tiess, G., 2010. **Minerals policy in Europe: Some recent developments**, Resources Policy, 35(3), 190198.

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3) Current methodologies

In this section, a comprehensive bibliography is done based on different mining residues applications and their characterization methods. Due to the objectives and methodologies used for characterization, five techniques are presented including different case studies from all around the world. The summary of techniques and their descriptions are presented in **Table 3**.

Table 3. Summary of techniques, their descriptions and their application areas

n°	Description	Known application areas
Technique 1	Environmental characterization: pollution detection and quantifying metals dispersion in the air, water and soil around the mining waste area	• Rio Tinto Mining area (Spain) • Sierra Minera de Cartagena (Spain) • Panasqueira mining area (Portugal)
Technique 2	Characterization of the historical mining wastes with drilling samples	• Cabeço do Pião Mining area (Portugal) • Harz Mountains Mining District (Germany)
Technique 3	Characterization of the historical mining wastes (stockpiles) without sampling	• Choghart iron mine (Iran)
Technique 4	Characterization of mining wastes using remote sensing	• Podgorica bauxite residuals (Montenegro) • Permian Meade Peak Mining Area (Idaho, US) • Iberian Pyrite Belt (Spain) • Leadville Mining District (Colorado, US)
Technique 5	Characterization of mining wastes with the direct link to the ore body and optimization programming	• Los Sulfatos deposits (Chile)

The complete descriptions of each technique, with specific information, method used and case studies, are presented in this section.

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Technique 1. Environmental characterization: pollution detection and quantifying metals dispersion in the air, water and soil around the mining waste area

This technique describes approaches of necessary sampling stations around the mine tailings and their need for environmental characterization of mining wastes. While identifying the location of the sample stations, different points should be considered such as:

- wind direction in the target area;
- presence of natural receptors, such as trees, rivers, etc.;
- presence of roads for trucks, other artificial structures;

The first application presented by **Castillo et al. (2013)** is a location distribution of soil samples for mining waste characterization made around Spanish Rio Tinto area, specifically considering the wind direction (**Figure 1.1**). Some specific locations around the mine wastes are considered:

- immediate vicinity of the main mine waste deposit (CEM);
- citrus exploitation near the mine wastes (RTF);
- village of Nerva (AYU);
- truck transfer station and main village roads (CTRA);
- far from the mining site, as background station (LD).

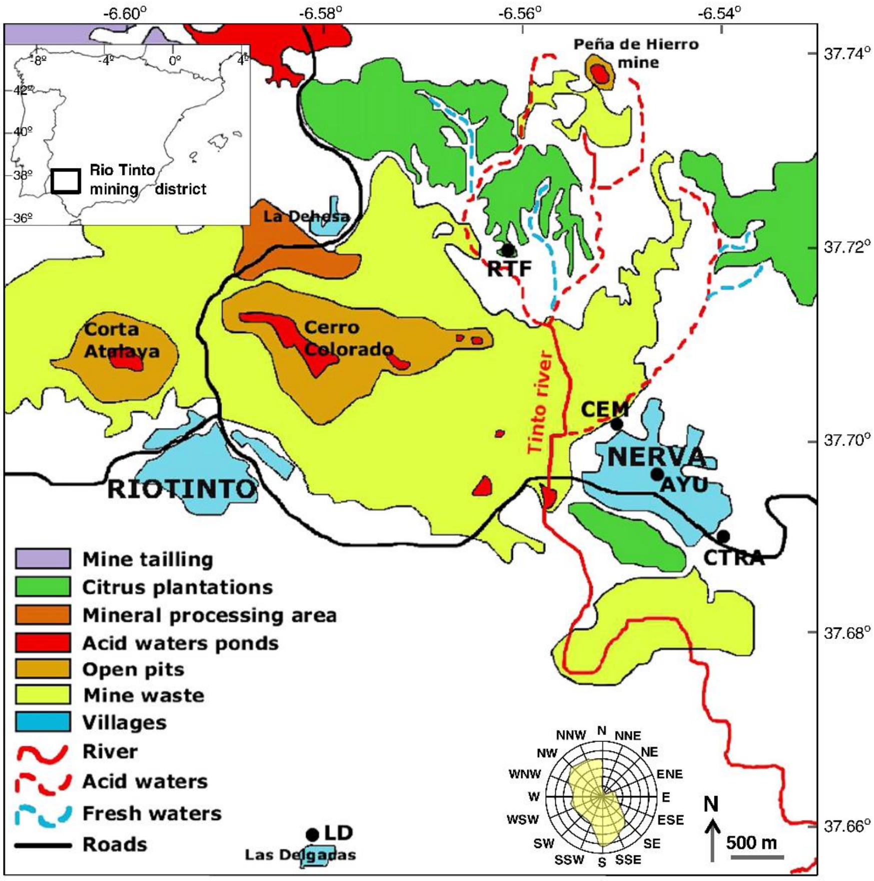

Figure 1.1 Localization of the soil sampling stations – RTF, CEM, AYU, LD and CTRA - inside the Rio Tinto Mining District, considering the wind rose diagram for the period March 2009 to February 2010 (from Castillo et al., 2013).

Due to the diversity of sample locations, the results showed how the different sampling stations can measure different metal concentration, due also to non-mining dust and absorption capacity of trees. However, samples were not enough to perform a complete mapping of specimens' distribution. Therefore, a complete sample grid, including different areas and features of the target zone, containing the diversity of samples locations, is the first and the most important points for characterization of mining wastes. In general, for environmental characterization (mainly pollution) from mining wastes, there are many applications, in which similar techniques are used.

Another application presenting the importance of sampling grid and location of measurement nodes, is done by **Alcolea et al. (2015)** on rainwater, to evaluate the influence of sulphidic mine wastes on rainwater quality (**Figure 1.2**).

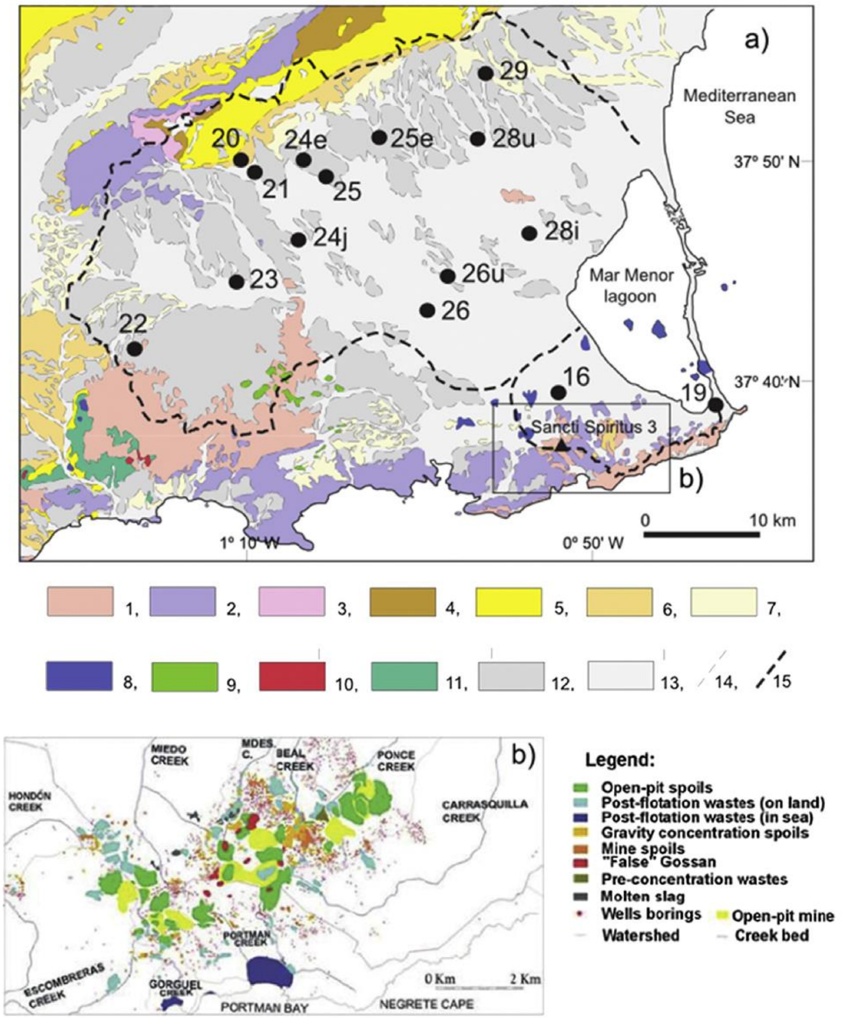

Figure 1.2. Localization of the rainwater sampling stations - 15 black dots - (a) besides the Sancti Spiritus Mining Area (b) for the period December 2004 to March 2008 (from Alcolea et al., 2015)

In the study, negative correlations between Cd, Pb, and Zn concentrations and distance from the mining tailings were found. On the other hand, positive correlations between Cu, As and Ni were present, with possible explanation on the use in pesticides. Generally, the study confirmed presence of metal pollutants in soluble fractions collected in rain-gauges. Moreover, at a distance of 20 km away from the tailing deposits, metals dispersion of mining wastes represents a minor environmental threat on the rainwater quality than the use of pesticides and nutritional supplements in agriculture.

A work from **Candeias et al. (2014)** focused on the estimation of spatial distribution of soil contamination due to mining wastes, by performing soil samples in a regular grid, for a total number of 122 samples around the mining area. In each sampling site, two types of samples were distinguished: topsoil and 15-cm depth

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soil. 47 samples were also collected outside of the mining area, as reference of no-contamination (**Figure 1.3**).

To map the pollution index in the mining waste area, the following steps were used:

- *estimation of the regional and local geochemical baselines*, to define the present state of non-polluted environment;
- *principal component analysis (PCA)*, to reduce complexity of large-scale data sets;
- *variography analysis*, to delineate the spatial structure of the investigated variables;
- *ordinary kriging estimation*, to create the map of estimated data, with estimation variance;
- *pollution load index*, to provide a quantitative pollution indicator, based on estimation results.

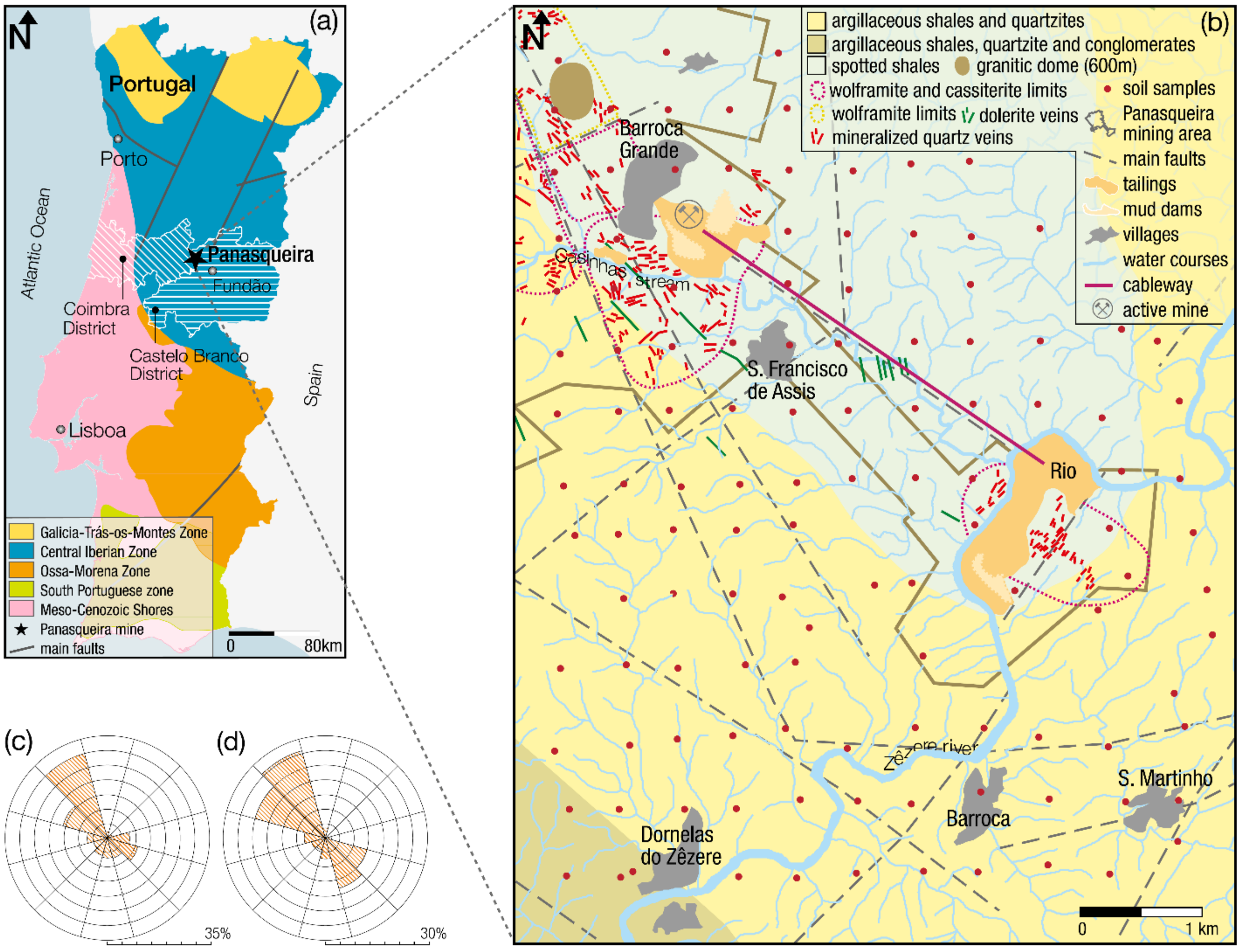

Figure 1.3 Localization of the soil samples grid - 122 red dots – (b) inside the study area (a), considering the wind rose diagram on the top of the Barroca mine (c), and on the top of the mountain 800 m north to the mine (d). (from Candeias et al. 2014)

The results of the environmental risk assessment showed that only possible contamination was present for Ag, Cu, Cd, Zn and As. Authors concluded with a comparison of similar studies around the world, stating that soil pollution of areas besides to mining activities should be further investigated, monitored and kept under control.

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Technique 1. Environmental characterization: pollution detection and quantifying metals dispersion in the air, water and soil of the mining waste area	
References	**Classification**
Castillo, S., de la Rosa, J.D., Sánchez de la Campa, A.M., González-Castanedo, Y., Fernández-Caliani, J.C., Gonzalez, I., (2013): Contribution of mine wastes to atmospheric metal deposition in the surrounding area of an abandoned heavily polluted mining district (Rio Tinto Mines, Spain), Science Total Environment, 449, 363–372.	Tailings Metals Environment Without RS RIS (MED-Spain)
Alcolea A., Fernández-López C., Vázquez M., Caparrós A., Ibarra I., García C., Zarroca M., Rodríguez R., An assessment of the influence of sulfidic mine wastes on rainwater quality in a semiarid climate (SE Spain) Atmospheric Environment 107 (2015) 85-94.	Tailings Metals Environment Without RS RIS (MED-Spain)
Candeias C., F. Ávila P.F., Ferreira da Silva E., Paulo Teixeira J., Integrated approach to assess the environmental impact of mining activities: estimation of the spatial distribution of soil contamination (Panasqueira mining area, Central Portugal), Environmental Monitoring and Assessment, 187, Article number: 135 (2015).	Tailings Metals Environment Without RS RIS (MED-Portugal)

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Technique 2. Characterization of the historical mining wastes with drilling samples

Historical tailings are generally unknown, however the metal concentrations should be high, since the dry methods of separation, especially before the use of processing steps (for example flotation, leaching, etc.), were generally inaccurate. To characterize the remained materials within these historical mining areas, textural, geochemical and mineralogical properties can be considered. Because in historical tailings, some information might be lost (such as the metals contents of the processing feed and final extraction yield), intensive sampling by drilling can be an option for getting information from the historical mining wastes.

Together with characterization of environmental parameters, there is an attention to investigate the possibility of valuable materials extraction in conjunction with mine waste management. Within the ERA-Min Project, tailings from Cabeço do Pião highlighted that studies and characterization of mine wastes are fundamental for economic, environmental and stability assessments, for selection between the two main alternatives: reprocessing or removal of tailings (**De Lourdes Dinis et al., 2019**). In this case, 41 samples were taken at two different depths in a regular grid inside the tailings dam for physical and chemical characterization of the wastes, including natural leaching test and screening tests for acid generation potential (**Figure 2.1**).

Figure 2.1. Localization of the soil samples grid – 41 red dots, disposed over 6 lines – inside the tailings dam of the Cabeço do Pião mine for the period November 2016 to December 2017 (from De Lurdes Dini, 2019)

The results of this study showed firstly the high environmental risk caused by the presence of tailings dam, with chemical composition of Fe, As, Zn, Cu and W within the tailing samples. Secondly, authors suggested, by a preliminary economic analysis, that reprocessing of Cabeço do Pião mine tailings to recover Zn and W and at the same time to remove As can be a promising solution from one side to solve the serious

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environmental and stability problems of the area and from the other side to tackle the depletion of Zn ores worldwide.

Another recent example of application, using this technique, is the "Bergwerkswohlfahrt" mine waste dump in the Harz Mountains historical mining area (**Kuhn and Meima, 2019**). These historical tailings were deposited between 1903 and 1931, with amounts varying between 25,000 and 40,000 tons per year and without any use of flotation.

There, direct push core drilling with plastic liners was applied as sampling method. In total, 16 cores were collected as part of three drilling campaigns. The drill pipes were rammed down to 4-8 m depth, thus interesting dump areas with ore processing residues at the surface (**Figure 2.2**).

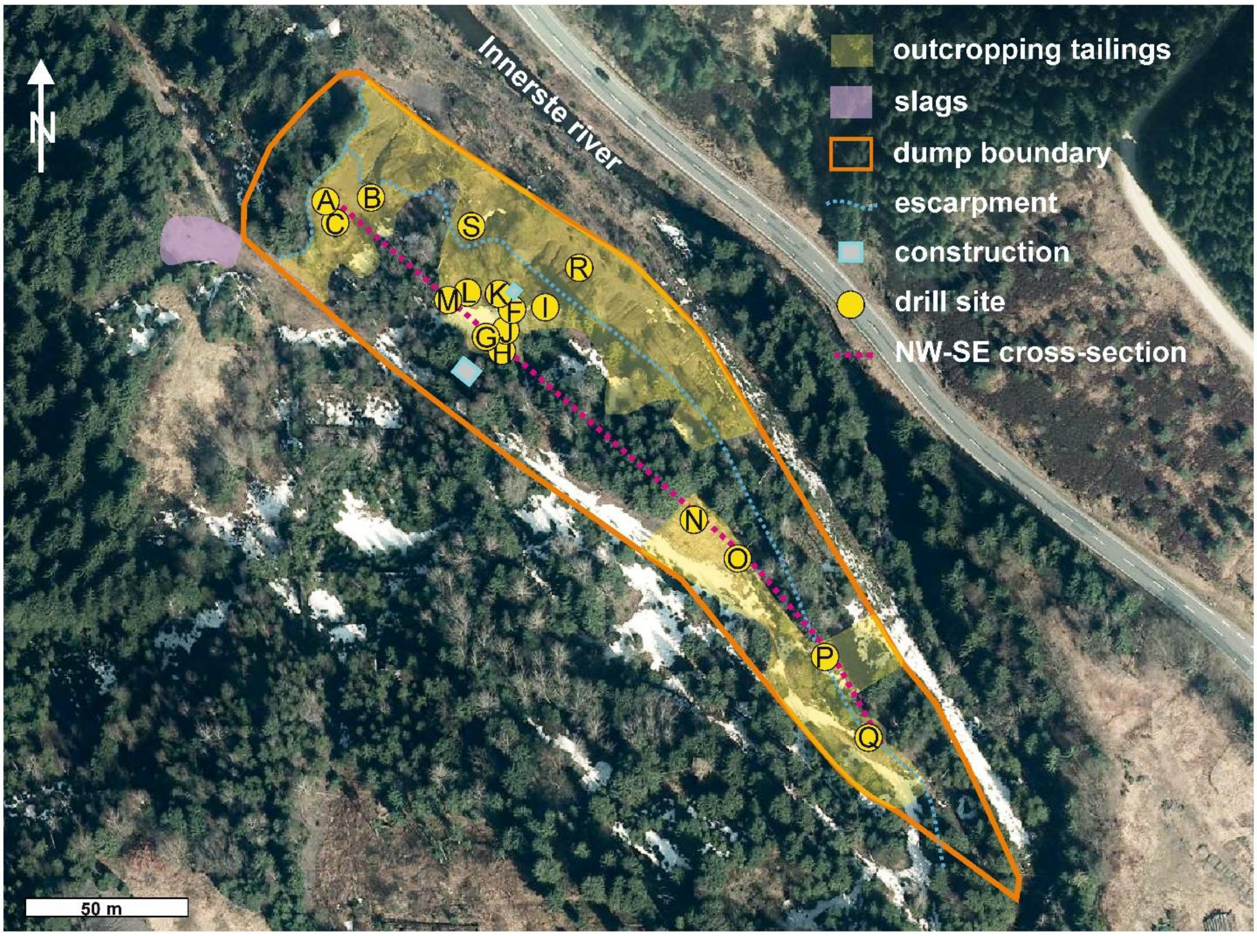

Figure 2.2 Localization of the drilling samples (yellow dots) over the historical and revegetated mining waste area (from Kuhn and Meima, 2019)

Samples taken by the cores were subjected to X-ray fluorescence (XRF), inductively coupled plasma-atomic emission spectroscopy (ICP-OES), laser ablation-inductively coupled plasma-mass spectrometry (LA-LCP-MS) and LIBS- core scanner methods in the lab.
Analyses of the core samples led to the definition of a spatial distribution of the valuable elements (Pb, Zn, Ag, Sb and Cu) along each drilling depth and over the surface area of the tailing.

Because of limited number of samples and lack of additional information, a three-dimensional correlation of specific layers between various cores was not possible, and even in adjacent drill cores it could be only hypothesized but not proven. As a consequence, variogram analysis was not reliable as well, because of high distances between samples, in limited numbers, since geostatistical modelling would have required a higher

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amount of drilling and sampling than what performed. Therefore, the preliminary resources estimation was calculated assigning to each zone of the dump the metal content of the core.

The study of such historical mining wastes proved the heterogeneous of such residues and their strong alternation of sand, silty sand, and clayey silt layers during the time. In the presented application, authors have shown that lead (Pb) and silver (Ag) can be considered of economic interest from the presented case-study.

Technique 2. Characterization of the historical mining wastes with drilling samples	
References	**Classification**
De Lurdes Dinis M., Fiúza A., Futuro A., Leite A., Martins D., Figueiredo J., Góis J., Vila M.C., Characterization of a mine legacy site: an approach for environmental management and metals recovery, Environmental Science and Pollution Research (2020) 27:10103–10114.	Tailings Metals Grade + Environment Without RS RIS (MED-Portugal)
Kuhn K.; Meima J.A. Characterization and Economic Potential of Historic Tailings from Gravity Separation: Implications from a Mine Waste Dump (Pb-Ag) in the Harz Mountains Mining District, Germany, Minerals 2019, 9, 303	Stockpiles Metals Grade Without RS Other European (Germany)

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Technique 3. Characterization of the historical mining wastes (stockpiles) without sampling

Grade and tonnage preliminary estimates over stockpiles can be performed based on historical studies of the mine, with particular reference to the mining excavation activities and trucks operations. An example of this technique can be found over the Chogart iron mine (Iran). In this case study, the grade-tonnage estimation of ore stockpiles (iron and phosphate) was performed on two separate stockpiles. The mine is located 125 km southeast of the Yazd, in central part of Iran. The estimated pre-mining reserve was 215.7 Mt on the basis of a 20% cut-off grade. The Choghart expansion project report put the remaining reserve of the deposit at about 167 Mt of which 140 Mt is mineable. Conventional open pit mining methods are used to extract this deposit at the rate of 3 million tons per year with an overall stripping ratio of 0.66:1. Due to the composition and degree of oxidation the iron ore of Choghart is classified into different groups (**Table 4**). The iron ore is of a low sulphur type, 90% of the ore body is non-oxidized (magnetite ore) and more than 65% of the reserve is of a low phosphorous type.

Table 4. Choghart pre-mining estimated reserve and ore classification (from ***Kasmaee et al., 2010****)*

Iron ore type	*Oxidation situation*	*Fe (%)*	*Fe_2O_3 (%)*	*FeO (%)*	*P_2O_5 (%)*	*SiO_2 (%)*	*SO_3 (%)*	*Fe/FeO*	*Reserve (Mt)*
Rich iron ore (low phosphorous- LG)	*Oxidized*	*63.81*	*81.15*	*9.07*	*0.16*	*3.07*	*0.10*	*7.03*	*4.70*
	Non-oxidized	*62.43*	*69.88*	*17.44*	*0.11*	*4.92*	*0.15*	*3.58*	*137.30*
Rich iron ore (high phosphorous-HP)	*Oxidized*	*54.16*	*70.83*	*5.94*	*3.39*	*4.97*	*0.25*	*9.12*	*17.10*
	Non-oxidized	*57.49*	*63.37*	*16.94*	*2.24*	*6.60*	*0.20*	*3.39*	*45.60*
Poor iron ore		*38.95*	*40.67*	*13.52*	*1.97*	*15.86*	*0.52*	*2.88*	*11.00*
Overall		*59.56*	*67.33*	*16.04*	*0.92*	*5.79*	*0.19*	*3.71*	*215.70*

For grade-tonnage estimation, historical studies of the mine were performed. The establishment of the stockpile at Choghart began in 1992 nearby the pit and continued until 2000. During the process of piling rocks, each pile was sampled to determine the composition in terms of Fe% and P% (**Kasmaee et al., 2018**). This sampling was carried out from the periphery of the monthly piles to the low grades LG and high grades HP stockpiles (**Figure 3.1**).

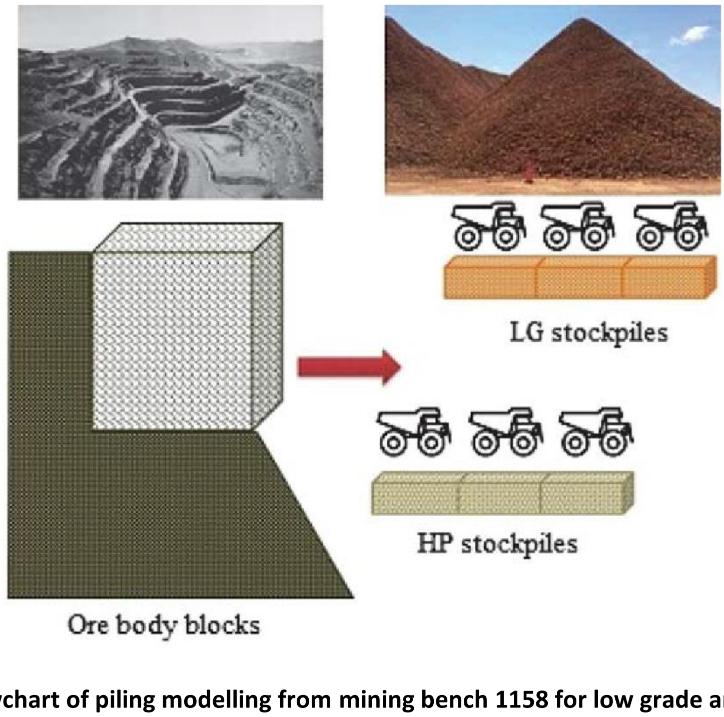

Figure 3.1. Simplified flowchart of piling modelling from mining bench 1158 for low grade and high grade stockpiles (from Kasmaee et al., 2018)

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The stockpile inventory was based upon pre-existing information gathered from various mining benches of the open pit, previously extracted. The information contained in the bench plans, such as Fe%, P%, volume and date of blasting, were assigned to each stockpile. Stockpiles can be large in size, contain different ore grades and the material can be cumbersome to sample. The importance of pre-existing records is a consequence of how difficult it is to "represent" a stockpile by sampling. By subsequent comparison, it was found that information derived from bench plans was more reliable than stockpile sampling itself. After statistical analysis and spatial variability of data, grade-tonnage volumes of stockpiles were estimated using Ordinary Kriging method, together with maps of iron and phosphorous variability (**Kasmaee et al. 2010**) (**Figure 3.2**).

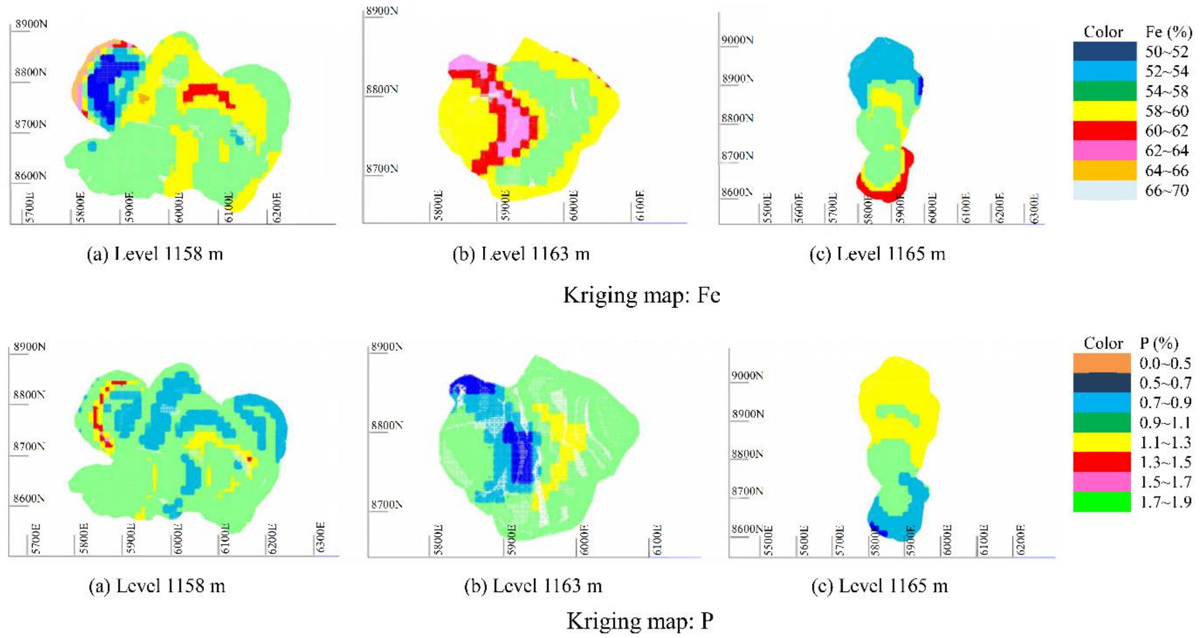

Figure 3.2. Maps of iron and phosphorous variability in three levels of HP stockpiles (from Kasmaee et al., 2010).

Curves and pile grade variabilities were considered to be of assistance to management decisions regarding sampling with a view to stockpile exploitation and the economic feasibility of waste materials as a new source (**Figure 3.3**).

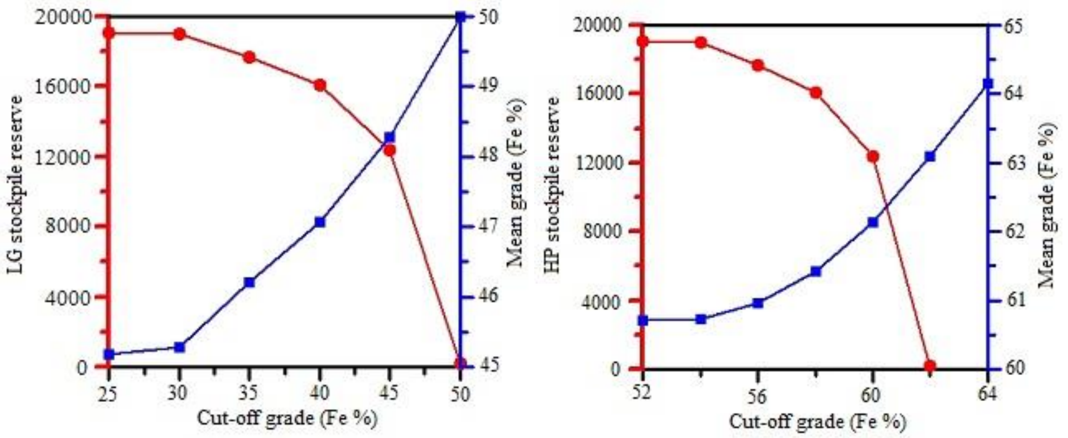

Figure 3.3. Grade-Tonnage curve for two simulated stockpiles (from Kasmaee et al., 2018)

The Grade-Tonnage curve of the stockpiles has demonstrated that, due to the high demand of raw materials and reducing the cut-off grade of Fe, both stockpiles can be considered as a new source of iron.

RawMaterials
Connecting matters
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Technique 3. Characterization of the historical mining wastes (without processing) without sampling	
References	**Classification**
Kasmaee S., Gholamnejad J., Yarahmadi A., Mojtahedzadeh H., Reserve estimation of the high phosphorous stockpile at the Choghart iron mine of Iran using geostatistical modelling, Mining Science and Technology 20, (2010) 0855–0860	Stockpiles Metals Grade Without RS RREM (Iran)
Kasmaee S., Tinti F., Bruno, R., Characterization of metal grades in a stockpile of an iron mine (Case study - Choghart iron mine, Iran), Rudarsko Geolosko Naftni Zbornik, Volume 33, Issue 2, February 2018, Pages 51-59.	Stockpiles Metals Grade Without RS RREM (Iran)

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Technique 4: Characterization of mining wastes using remote sensing.

Earth observation (EO) tools can be very useful for the preliminary mapping, quantification and monitoring of the mining residues, usually abandoned, in harsh environment, and with limited possibilities for full sampling campaigns. EO (active sensors) measures the portion of incoming solar radiation that is reflected by surface materials across several spectral bands. Because spectral patterns of reflectance for common land-cover types such as water, bare soil, and productive vegetation are well-constrained, a remotely sensed image can be used as an input for classification algorithms, which can indicate the presence of mining, infrastructures, stockpiles and tailings at the time of image acquisition. The EO main potentials are:

- large number of free and easy to access EO data;
- continuity of data in time with subsequent continuous land monitoring.

Outside the mining industry, academics and civil society organizations have employed EO to analyse the impacts of mining for a variety of purposes. In this framework, majority of analyses have addressed mapping pollution and environmental variables in both active and abandoned mining areas, in combination with imaging spectroscopy for directly identifying minerals and soils containing pollutants as an indicator of contamination. The review done by **Werner et al. 2019** is a quite exhaustive document on the use of remote sensing as a guide for sampling and the environmental monitoring to demonstrate the impact of mining activities. All studies have proved that traditional old mining activities significantly affect the surrounding environment., because of the lack of policies concerning the handling of tailings materials, leading to their massive redistributions downstream from their original dump site to the rivers. On the other side, more recent mining activities are suggested to strict regulations, which, together with raising awareness, led to remediation and constant monitoring of closed mining sites. As examples, **Ferrier (1999)** worked on waste rock and tailings produced from mining activities, focusing on environmental pollutions of materials and trace elements of tailings using airborne mapping and high imaging spectrometer data, for the Rodalquilar mining area, Spain. On the same mining site, more recently **Choe et al. 2008** have used the spectral variations associated with the presence of heavy metals in stream sediments to characterize the distribution of areas affected by heavy metals (**Figure 4.1**)

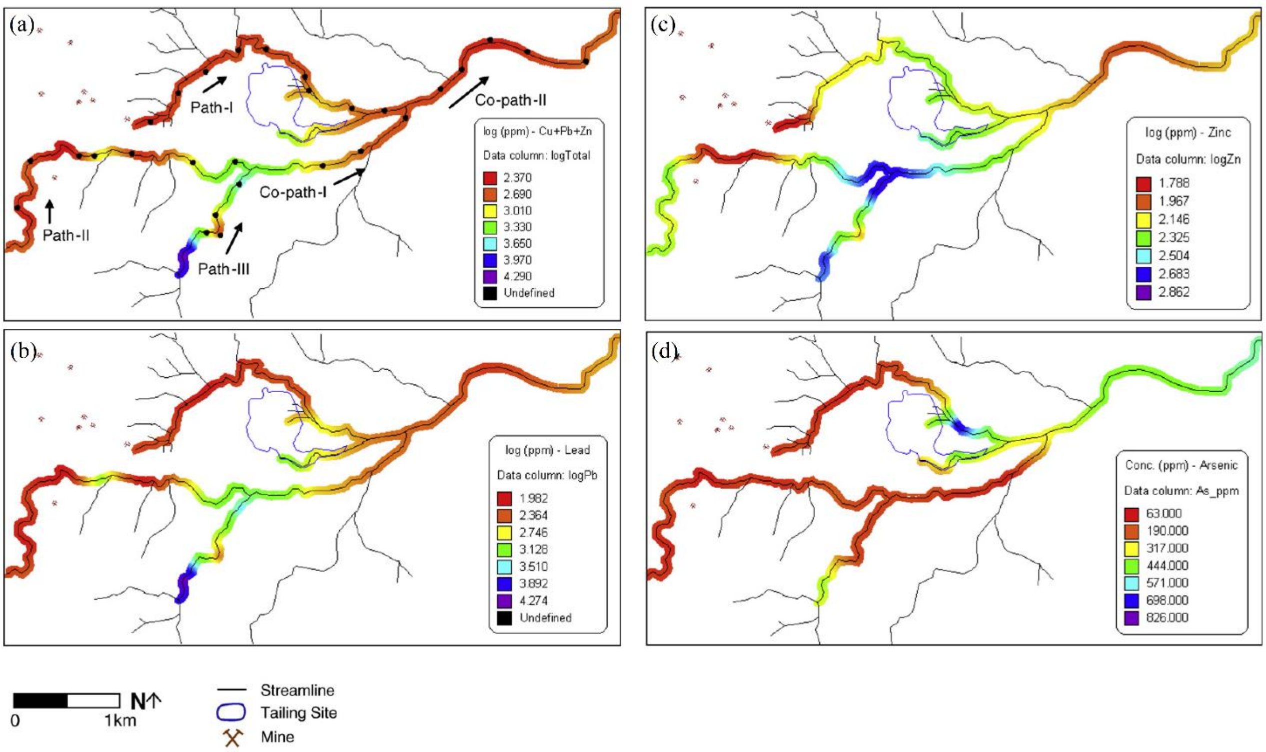

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Figure 4.1. Streamlines and maps of concentration of heavy metals (Pb, Zn and As) obtained by comparison between samples and hyperspectral images for the Rodalquilar mining area, Spain.

The studies showed how the dispersion of contaminated material can be obtained from imaging spectrometer data. The considered spectral absorption feature parameters showed the potential to detect heavy metals, and the image-derived spectral parameters showed some efficacy in screening the stream lines affected by heavy metals to detect environmental pollution.

As a different example, **Pascucci et al**., in 2012 used imaging spectroscopy in combination to EO to map red mud dust waste in a bauxite tailings dam (red mud), located near Podgorica in Montenegro (**Figure 4.2**).

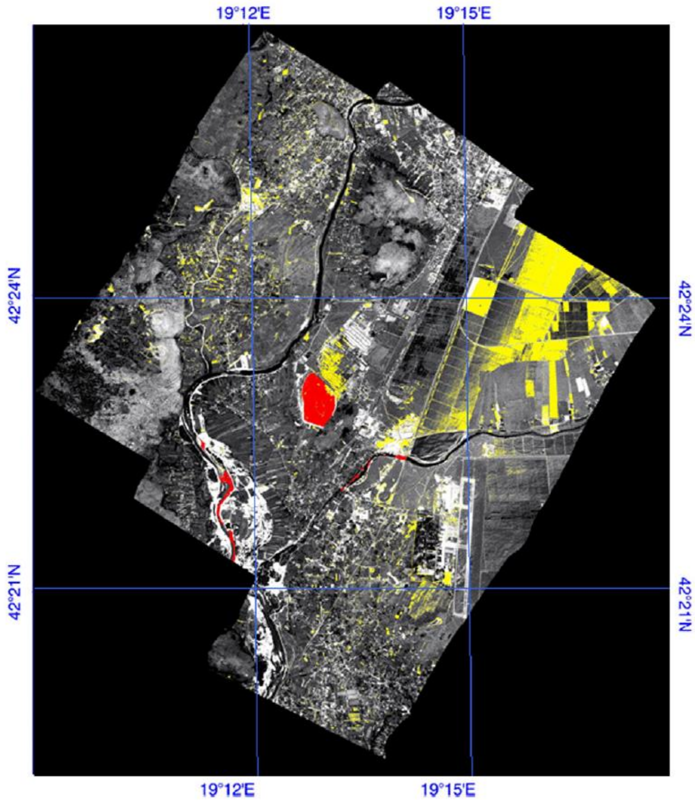

Figure 4.2. Red Dust (RD) map as attained by applying ISODATA clustering to the chosen IC bands; yellow and red colours show the RD on soils and the RD on water classes, respectively (from Pascucci et al, 2012).

Various researchers have used EO to map sediments redistributed in the rivers downstream mining areas, and to characterize the mineralogical variability. Already in 1997, **Farrand W.H., and Harsanyi J.C**. used Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) to detect pollution in the Coeur d'Alene river, Idaho, due to the silver underground mines near Kellogg, Idaho. Specifically, they used the constrained energy minimization (CEM) technique to determine the ferruginous elements of mining origin in the river (ferrihydrite). Using a specific constraint, CEM uses a finite impulse response (FIR) filter to pass through the desired target while minimizing its output energy resulting from a background other than the desired targets. A correlation or covariance matrix was used to characterize the composite unknown background. A similar, more recent, work, again using AVIRIS hyperspectral imagery calibrated by field observation, was done by **Mars J. C. and Crowley J. K.** in 2003, over a phosphate mining zone of Idaho. In this work, metal pollutant concentrations on both vegetation and water were mapped. Specifically, eighteen mine waste dumps and five vegetation landcover types in the southeast Idaho were analysed and mapped (**Figure 4.3**). Relative amounts and directions of surface water flow associated with each mine dump were analysed using digital elevation data and combined with information on stream gradients and riparian vegetation cover, providing spatial information on variations in selenium concentrations.

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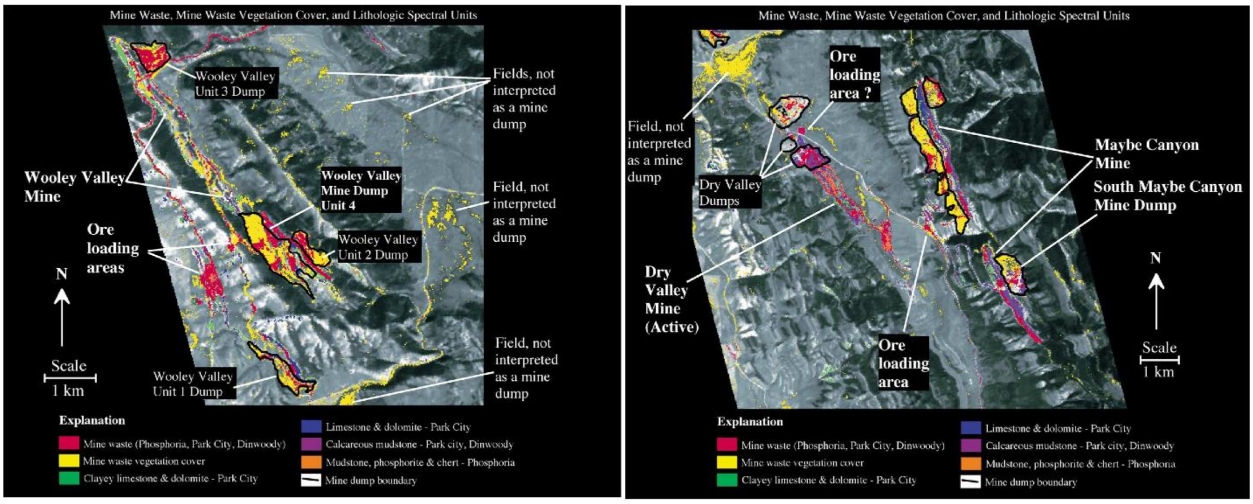

Figure 4.3. AVIRIS image of the Wooley Valley Mine (left) and the Maybe Canyon Mine (right) with lithologic and mine waste spectral units, and interpreted mine dumps mapped in black lines (from Mars and Cowley, 2003).

Other applications concern the use of the airborne hyperspectral images over the Odiel River path on 17 July 2005, 4 August 2008, and 13 August 2009 (**Buzzi et al., 2014**). The airborne hyperspectral sensor used has 128 wavebands from 436 to 2485 nm with a spectral resolution of 15 nm in the 436–125 nm wavelength range, 13 nm in the 140–180 nm wavelength range and 17 nm in the 195–248 wavelength range. Over the abandoned mining sites of the Iberian Pyrite Belt, it was possible to detect the mineral changes (due to the weather) and anthropic interventions (due to remediation of mining sites) across the years (**Figure 4.4**).

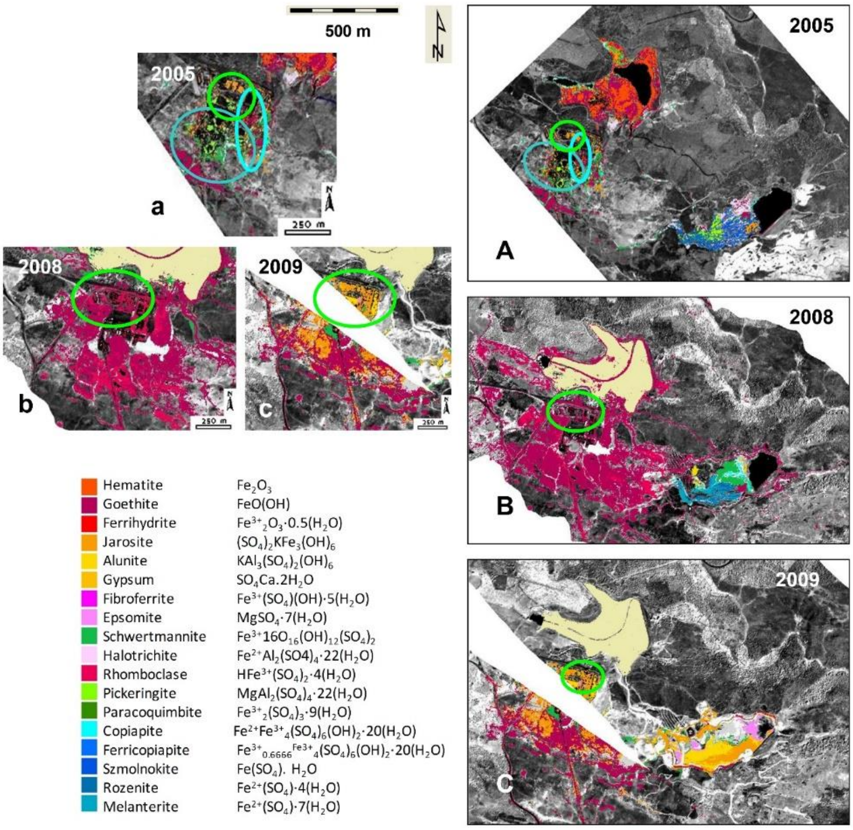

Figure 4.4. Mineral variations in the period 2005-2009 in the mining site of Sotiel, Spain, obtained by the analysis of hyperspectral data (from Buzzi et al., 2014)

The Hymap 2005 flight pictured the state of the facilities before any recovery activity, while the Hymap 2008 flight showed the ash dam covered by dry grass, completely recovered, and the surroundings clean, free from any pyrite weathering product, which was mechanically cleaned over the dumps. On the other hand, oxidation persisted due to the machinery movement. Finally, the Hymap 2009 flight evidenced that the mud from the mill tailings dam was removed, and the state of oxidation in the crusts started to decrease, due to the dismantling of ore processing plant, buildings and machinery.

Finally, imaging spectroscopy can be used also to map acidic rock drainage, as for the example of **Swayze et al. in 2000.** The spectral mapping of the Venir pile traverse wastes within the California Gulch Superfund Mining Site near Leadville (CO, USA) was obtained by the use of AVIRIS. Specifically, the study showed how detecting jarosite at the surface have an elevated potential for proving the presence of acidic water. However, areas lacking jarosite at the surface may still generate acidic drainage (**Figure 4.5**).

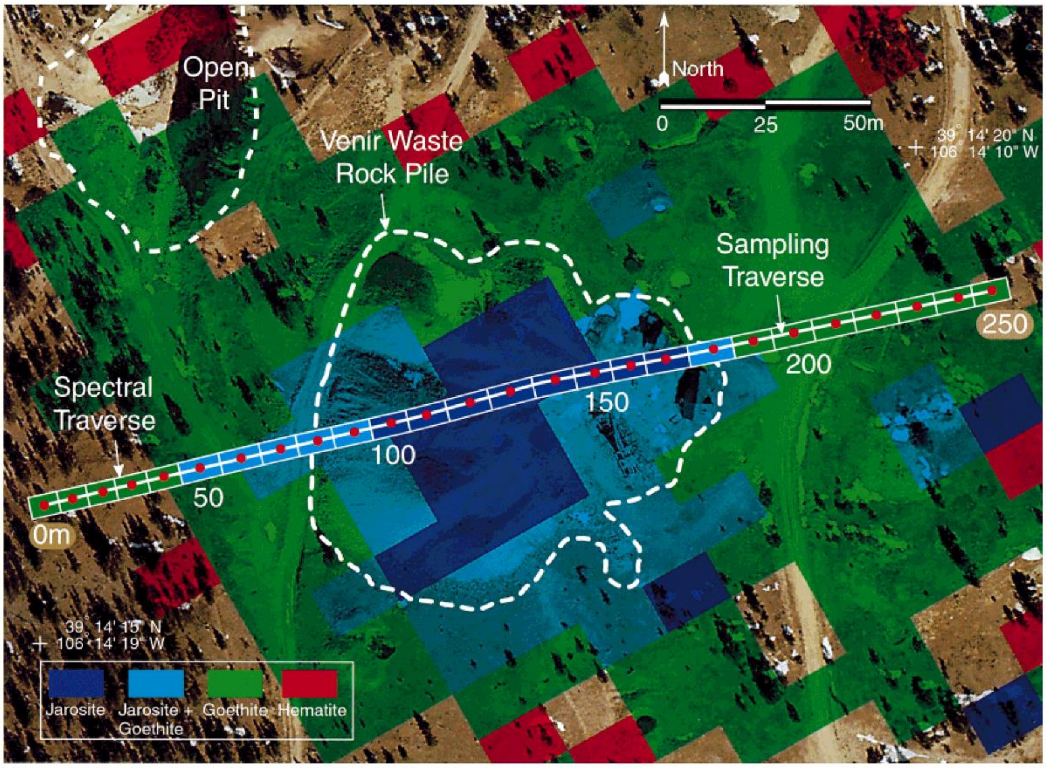

Figure 4.5. Spectral traverse and AVIRIS mineral maps overlaid on a high-spatial-resolution aerial photograph of the Venir traverse mine waste (from Swayze et al., 2000)

Authors concluded that in case of remediated mine waste, the detection of acid mine drainage can be hindered by the presence of neutral material and vegetation. On the other hand, vegetation growth and features, detectable by remote sensing, can act as indicators of presence/absence of acid drainage and pollutants.

Using imaging spectroscopy allows identifying, delineating and monitoring environmental signatures associated with mined and unmined mineral deposits. The spatial mineralization patterns are critical for accurate interpretation of climate change trends, metal contamination estimations or acid drainage prediction. Maps derived from individual subscenes and processed using independent procedures broadly agree with each other with respect to changes in oxidation and dehydration mineral phases. Areas covered by vegetation types and other obscuring land use/cover types had to be masked in order to achieve reasonable results for pyrite oxidation mineral trends.

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There are strong limitations to validate mapping data using in-situ samples (with their conventional chemical analysis), due to its high spatial heterogeneity and fast temporal mobility. Spectral behaviour trends extracted from the images and in the laboratory from geological sample evaluations can provide reliable indicators for monitoring contamination from mine wastes. The challenges and limitations mapping pyrite oxidation products over mine waste dealing with preprocessing procedures, heterogeneous mineral mixtures and spectral diagnostic methods are already widely discussed.

Technique 4: Characterization of mining wastes using remote sensing	
References	**Classification**
Choe E., Van der Meer F., Van Ruitenbeek F., Van der Werff H., Boudewijn de Smeth B., Kim K.W., 2008. Mapping of heavy metal pollution in stream sediments using combined geochemistry, field spectroscopy, and hyperspectral remote sensing: A case study of the Rodalquilar mining area, SE Spain. Remote Sensing of Environment. 112, 3222–3233	Tailings Metals Environment With RS RIS (Spain)
Ferrier G., 1999. Application of Imaging Spectrometer Data in Identifying Environmental Pollution Caused by Mining at Rodaquilar, Spain. Remote Sensing of Environment, 68, 125-137	Tailings Metals Environment With RS RIS (Spain)
Pascucci, S., Belviso, C., Cavalli, R.M., Palombo, A., Pignatti, S., Santini, F., 2012. Using imaging spectroscopy to map red mud dust waste: the Podgorica aluminum complex case study. Remote Sens. Environ. 123, 139–154	Tailings Metals Environment With RS RIS (Montenegro)
Werner T.T., Bebbington A., Gregory G., 2019, Assessing impacts of mining: Recent contributions from GIS and remote sensing, The Extractive Industries and Society 6 (2019) 993–1012	Tailings + Stockpiles Metals Environment + Grade With RS RIS+RREM
Mars J. C., Crowley J. K., 2003, Mapping mine wastes and analyzing areas affected by selenium-rich water runoff in southeast Idaho using AVIRIS imagery and digital elevation data, Remote Sensing of Environment 84 (2003) 422–436	Tailings Metals Environment With RS Other non-European (USA)
Farrand W.H., and Harsanyi J.C., 1997, Mapping the Distribution of Mine Tailings the Coeur d'Alene River Valley, Idaho, through the Use of a Constrained Energy Minimization Technique, Remote Sensing of Environment 59:64-76	Tailings Metals Environment With RS Other non-European (USA)
Buzzi J., Riaza A., García-Meléndez E., Weide S. and Bachmann M., 2014, Mapping Changes in a Recovering Mine Site with Hyperspectral Airborne HyMap Imagery (Sotiel, SW Spain), Minerals 2014:4	Tailings Metals Environment With RS RIS (Spain)
Swayze G.A., Smith K. S., Clarck R. N., Sutley S. J., Pearson R. M., Vance J. S., Hageman P. K., Briggs P. H., Meier A. L., Singleton M. J. and Roth S. (2000) Using Imaging Spectroscopy to Map Acidic Mine Waste, Environmental Science & Technology 34, 47-54	Tailings Metals Environment With RS Other non-European (USA)

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Technique 5: Characterization of mining wastes with the direct link to the ore body and optimization programming.

According to several researches done on mining waste managements, the current definition of a single mineralized zone in a deposit characterization, the typical approach of mining industry, is not suitable to explore the presence - and possibility of economic recovery - of trace critical metals. In fact, in some cases, thinking of critical raw materials recovery from mining waste is not appropriate enough, however, there should be some pre-consideration while excavating the ore body. To address this issue, **Velasquez et al. (2020)** proposed the adoption of the metal-zone concept, in which the metal-bearing minerals are characterized directly in the ore body from a metallogenic approach. Therefore, by characterizing and identifying the metal zones for each element of interest in the ore body, it is possible to design the processing of the main ore, considering the potential for selective-metal mining, moving from standard single-metal tracking to multi-metal tracking (**Figure 5.1**).

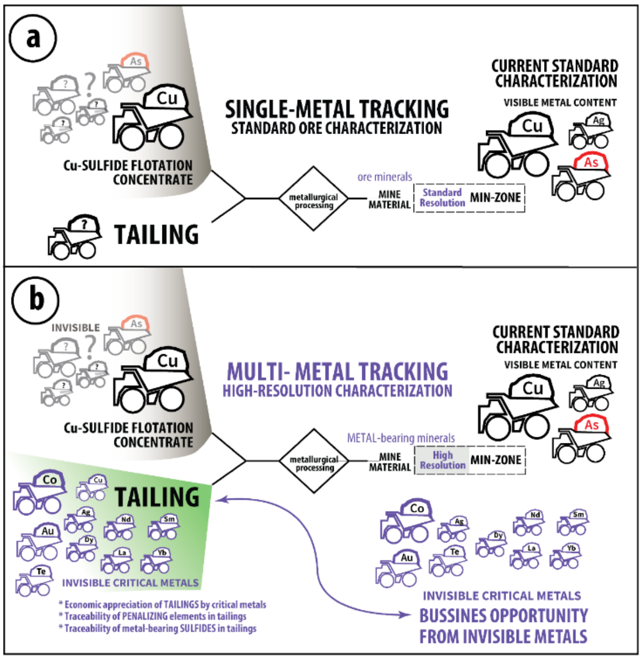

Figure 5.1. Multi-Metal Tracking approach in comparison to traditional single-metal tracking (from Velásquez, 2020).

The advantage of improved knowledge of the feed (in the processing) can be declined in the following ways:

- due to better control of the processing feed, by adding dedicated metallurgical processing for trace metals of interests;
- due to better control of the processing exit, by dividing the wastes in different tailings, according to the trace metal content;
- easier management of tailings and reduction of metals pollution.

Velasquez et al. (2020) suggested the application of this approach in a porphyry copper mine in Chile, where they applied high resolution characterization over different zones of the ore deposit, thus identifying zones with higher content of:

- in the pyrite: cobalt (up to 24,000 ppm), gold (up to 5 ppm);
- in the monazite: lanthanum (up to 4,000 ppm);
- in the molybdenite: rhenium (up to 514 ppm), gold (up to 31 ppm), tungsten (up to 31 ppm);

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- in the chalcopyrite and arsenical pyrite: gold (up to 4 ppm), silver (up to 22 ppm) and tellurium (up to 14 ppm);
- in the bornite: silver (up to 316 ppm), tellurium (up to 129 ppm) and gold (up to 1 ppm)

The conclusion is that a tailing enriched in pyrite is an easy prospect to explore for critical metals, which occur as mineral inclusions, both as visible grains and invisible nano-particles.

Moreover, the cost of mining, crushing and grinding stages can be developed on the bulk mine-mineral, and accounted into the copper production investments, which would imply that only the value for implementing additional operation units must be imputed to the by-products budget.

Technique 5: Characterization of mining wastes with the direct link to the ore body and optimization programming	
References	**Classification**
Velásquez, G.; Carrizo, D.; Salvi, S.; Vela, I.; Pablo, M.; Pérez, A. Tracking Cobalt, REE and Gold from a Porphyry-Type Deposit by LA-ICP-MS: A Geological Approach towards Metal-Selective Mining in Tailings. Minerals 2020, 10, 109.	Tailings Metals Grade Without RS RREM (Chile)
Velásquez, G.; Estay, H.; Vela, I.; Salvi, S.; Pablo, M. Metal-Selective Processing from the Los Sulfatos Porphyry-Type Deposit in Chile: Co, Au, and Re Recovery Workflows Based on Advanced Geochemical Characterization. Minerals 2020, 10, 531.	Tailings Metals Grade Without RS RREM (Chile)

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4) Proposed methods

The methods and case studies presented have shown how some tools can be efficiently used together for mineral wastes characterization. On the other hand, the type of waste and its mineralogy determines the preference on some applications with respect to others.

In the present chapter, the mining wastes are subdivided in categories due to the reviewed information. For each of them, some integrated methods are proposed for characterization of mining wastes due to raw materials strategy adaptations (**Table 5**). It is important to note that due to the large variety of parameters directly linked to the mining wastes (such as geology, excavation methods, piling methods, weather conditions, etc.), practical characterization of each case-study should be considered as a unique procedure adapted to the condition of the mining waste in question.

Table 5 - Categories of mining wastes

N°	Main feature	Category description
Category 1	Abandoned stockpile	Stockpiles from abandoned mines
Category 2	Active stockpile	Stockpiles from active mines
Category 3	Active tailing	Tailings from active processing plants
Category 4	Abandoned tailing	Flooded historical tailings
Category 5	Revegetated mining wastes	Revegetated historical stockpiles and tailings

Category 1: Stockpiles from abandoned mines

Mining wastes in this category, in general, are in the form of the mixed soil and rocks accumulations (depending on the type of stockpiles if they have passed through crushing or not), besides mining sites. Their mineralization across years has been modified by weather, with potential occurrences of metals' leaching. In some cases, these artificial hills have become part of the landscape and even recognized as historical industrial heritage. Across the years, the smallest grains have usually been transported by wind and weathering around the mining areas, causing pollution.

For these specific types, the proposed steps for characterization is:

- Historical studies of the mine-life, to understand the cut-off grade at the time of the mine exploitation. This will allow reconstructing and simulating the mine cycle, so to perform probabilistic analysis on the mineral contents of the stockpile;
- On the basis of the historical studies results, specific sampling (possibly not only superficial but reaching the stockpile depth) on the homogenous target areas individuated by probabilistic calculation;
- Over the stockpile site, topographic measurements for volume reconstruction and spectroradiometer for further correlation with remote sensing data can be performed;
- Use of the collected information to reconstruct the grade -tonnage characteristics of the stockpile. Different estimation methods can be used. Moreover, the interaction of in-field measurements with remote sensing tools can be considered as additional value.

Category 2: Stockpiles from active mines

When dealing with active mines, the current cut-off grade determines separation between high-grade and low-grade stockpiles. Characterization of the active stockpiles (mostly low-grade) can be made punctually

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during mine operations, by estimating the grade-tonnage curve on the basis of the limit cut-off and its variations across time. A detailed report of the stockpiles' modification (according to the load and unload cycles) should be conducted. Satellite imagery can be used to monitor the progress (construction, extraction) of volume and shape of both high-grade and low-grade stockpiles. Moreover, when dealing with active mines, the characterization of metal-bearing minerals directly in the ore body can be a supporting tool to improve the estimation of quantities of different metals led to the stockpiles. For all these reasons, knowing the mine-life planning is fundamental for a correct determination of metal variations within stockpiles.

Category 3: Tailings from active processing plans

Characterization of tailings from active processing is similar to those of active stockpiles. Additionally to the mine-life information, it is necessary to know the processing scheme, too. Material content of wastes from the processing plans depends on:

- type of processing, which defines the target extracted materials (main elements and by-products);
- type of feed: small variations of feed can cause variations of processing results.

Analyses on processing tailings must be done on the material at the exit of the process. In most cases, tailings are treated (filtration and neutralization) before long-life storage. for example, with acid leaching, tailings are neutralized with caustic or lime to avoid or reduce any upcoming pollution. Based on the results of analyses, and after selecting material classification and metal content thresholds, wastes should be assigned to different zones of the tailing pools. The extent, height and volume of each homogeneous zone should be kept under control. Satellite images, as well can be used for monitoring, thus providing a continuous update of the tailings and their variations. A regular sampling (randomly from different zones of tailings) can be done to check the coherency of metals content derived by initial prediction, remote sensing analysis and local estimates.

Category 4: Flooded historical tailings

Characterization of flooded historical tailings (waste dams) is complex, but very sensitive and important because of:

- subjection to weathering, causing variations of water content, acid mine drainage and chemical reactions in the dam and its surroundings across the year;
- difficulty in sampling submersed levels of tailings;
- high uncertainty in using earth observation historical images due to water reflectance affecting results;

On the other hand, chemical characterization of the water (both inside tailing dam and discharged outside) can be easily done and provide information over metal content of tailings. Moreover, additional data collection and monitoring using satellite imagery can provide an efficient technique to characterize the dust dispersion and pollution parameters around the tailing area. The satellite imagery data can be combined with data from surface sampling of tailings and chemical analysis of the water to map the metal content of tailing dam over the time. Finally, tailings characterization can be accompanied by an historical study of the processing plan, which led to production of the specific type of wastes and possible remained raw materials within them.

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Category 5: Revegetated historical stockpiles and tailings

The revegetated mining wastes are those historical stockpiles and tailings which are relating to the ancient mining activities and are transferred into the natural features (ex. Hills, natural forests, vegetated landscapes) during the time. Currently, remediation and vegetablization of tailings are performed in some cases, to reduce their visual impact and to increase physical stability. Their characterization depends mainly on:

- the type of waste management inside the mine life, which provided the excavated ground (gangue) formed a stratum over tailings for further revegetation.
- the age of the mine, leading that natural vegetation have progressively invaded the ancient mining area.

In both cases, nowadays stockpiles and tailings are in the form of a seminatural hills and features, which probably has caused metal leaching across years, with subsequent water pollution. On the other hand, metal contents should be high, due to the use of low efficient techniques for metal separation in ancient times. In case of water quality monitoring and a high amount of metal concentration, it is possible to consider a water treatment plant besides the mining site.

Characterization of these stockpiles and tailings can be only partially done by getting information over the mine life, usually found incomplete or even missing. Moreover, the earth observation datasets just cover recent times, thus when revegetation had already abandoned.

In this situation, a set of direct and indirect measurements can be collected:

- Regarding direct measurements, there is the need of taking multiple surface and deep samples over a large area of the ancient mining sites, to investigate the three-dimensional varieties of materials.
- Regarding indirect measurements, they can be:
  - chemical and physical analysis on surface water and groundwater reaching the aquifers of interest by piezometers and wells;
  - air pollution sampling;
  - Measurements over influence of metals over vegetation growth. In this case, geochemical and biological analyses over trees, other types of vegetation and sediments can be accompanied by remote sensing. The aim should be detecting zones of homogenous features of vegetation and other environmental effects around the historical mining area. In this way, plant ecological functions can be integrated with available radiometric data of mining area associated with the principles of electromagnetic spectrum.

The volume, tonnage and metal content of the historical tailings and stockpiles can then be reconstructed by estimation techniques, always considering the varying nature and support of the different measurement types.

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5) Discussion and Conclusions

Characterization of mining wastes (tailings and stockpiles) are very well known as a fundamental step in mining wastes managements, not only to get a comprehensive vision for the possible raw materials recovery, but also for any kind of environmental issues. Different techniques are presented through this report using various types of samples or even techniques without sampling.

In general, to consider the mining residues as precious source of raw materials, firstly, all active and abandoned sites should be detected, studied, defined and classified due to the described parameters. Then, due to the possibilities of historical data collection, sampling, and the remote sensing data interaction, an efficient method can be selected to characterize the metals, non-metals and environmental parameters.

In this step, the existence of CRMs can be confirmed and the effects of any toxic or non-toxic but influencing the environmental features (such as air, water, soil or vegetation) can be highlighted. In the case of any environmental effect, active assessments and monitoring can be performed using remote sensing techniques. However, even considering environmental risk or not, mining wastes can be considered as potential reserves of raw materials and specifically CRMs.

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6) European Commission legislation for mining wastes management

Based on **Directive 2006/21/EC** of the European Parliament and the following **Decision 2009/360/EC**, the technical requirements for characterisation and management of mining wastes are presented in this part.

- **Background information**: review and understanding of the general background and objectives of the extractive operation. Therefore, there is a need of collecting general information about:
    - mining prospecting, extraction, or processing activity;
    - type and description of method of extraction and process applied;
    - nature of the intended mine product.

- **Geological background of deposit to be exploited**: Identification of the waste units to be exposed by extraction and processing by providing relevant information on:
    - nature of surrounding and host rocks, their chemistry and mineralogy, including hydrothermal alteration of mineralised rocks;
    - genesis of deposits, including mineralised rocks or rock-bearing mineralisation;
    - mineralisation typology, mineralogy, the chemical and physical properties such as density, porosity;
    - particle size distribution, water content, covering ore and gangue minerals, hydrothermal newly-formed minerals;
    - size and geometry of deposit;
    - weathering and supergene alteration from the chemical and mineralogical point of view.

- **Nature of the waste and its intended handling:** Description of the nature of all the wastes occurring in each prospecting, extraction and processing operation, including overburden, waste rock and tailings. The necessary information should be provided on the following elements:
    - origin of the waste in the extraction site and the process generating the target wastes, such as prospecting, extraction, crushing and milling;
    - concentration of materials within the wastes;
    - volume of the wastes' materials;
    - description of the waste transport system;
    - description of the chemical substances to be used during treatment;
    - classification of the waste according to Commission decision 2000/532/EC (1), including hazardous properties;
    - type of intended waste facility, final form of exposure of the waste and method of deposition of the waste into the facility.

- **Geotechnical behaviour of the waste:** Identification of the suitable parameters for assessing the intrinsic physical characteristics of the waste, taking into account the type of waste facility. Relevant parameters to be considered are:
    - granulometry;
    - plasticity;
    - density and water content;
    - degree of compaction;
    - shear strength and angle of friction;
    - permeability and void ratio;
    - compressibility and consolidation.

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- **Geochemical and chemical characteristics and behaviour of the waste:** Specification of the chemical and mineralogical characteristics of the waste, and of any additives or residuals remaining in the waste. Prediction of drainage chemistry over time for each type of waste, taking into necessary account its intended handling. In particular:
    - evaluation of metals, oxyanion and salt leachability over time by pH dependence leaching test, and/or percolation test and/or time-dependent release and/or other suitable testing;
    - for sulphide-containing waste, static or kinetic tests shall be carried out in order to determine acid-rock drainage and metal leaching over time.

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6.1 Application of European Mining Waste Directive to Project Countries

- **Italy**

Italy transposed the **Directive 2006/21/EC** on the Management of Wastes from Extractive Industries by the **D.lgs 117/2008**, which distinguish the extractive wastes from other types of wastes. The wastes classified under this law must satisfy two conditions:

- being of extractive origin;
- being stored within the mining area.

Therefore, the excluded wastes are the ones related to collateral activities (batteries, oil, machinery, etc.) and those transported and disposed far from the mining site. Moreover, stockpiles within the mine sites are considered inside this law, while the tailings obtained from the processing plant (in the case of being far from the mine site) are outside the rule. According to the **DL 69/2013**, the extractive wastes from mining sites of national interest, after collecting the proper information over the presence of metals and pollutants, and after chemical treatment when necessary, must be reused to fill the mining excavation voids, realize the dams and trenches and restore the environmental quality of the mining areas. This rule is valid for present and future mining activities (thus it must be integrated in the waste management plan of the mining site). Moreover, the law includes the abandoned mining sites, in the case of environmental restoration when necessary. Based on the Directive and its application to the Italian context, the extractive companies must guarantee the environmental protection and safety of the mining area, during the activities and after the closure, too (**Serra et al., 2014**). Therefore, the mining plan must include continuous environmental characterization, even after the mine closure, while securing the area. Several information related to mine closure must be provided, such as:

- the description of securing operations and the management phases of closure and post-closure of the mine;
- the geotechnical characteristics of the dams and piles;
- the procedures for monitoring and control;
- the results of periodic chemical and mineralogical analyses.
- the measures taken to prevent air, water and soil pollution.

All these considerations lead to a continuous environmental monitoring of the mining sites and mineral characterization of mining residues. Therefore, a better knowledge of the wastes will be gained including:

- localization and geometry;
- tonnage and volume of mining residues;
- concentration of main metals classified as pollutants.

Moreover, all chemical reactions inside the tailings (both of natural and anthropic origin), modifying their composition, are monitored for several years.

Today in Italy, there are no specific laws about recovery of raw materials from extraction wastes, thus the second use of mining residues is currently not foreseen or planned by extractive companies, and neither as an economical option for historical mining areas. In fact, the **DL 69/2013** imposes to use the non-hazardous extractive wastes (related to the environmental restoration), as a considerable on-site environmental geotechnical intervention. To overcome this barrier for the recovery of precious minerals, a recent intervention is proposed to formally classify the abandoned stockpiles and tailings as secondary raw materials. Today, this is a major challenge for the Italian extractive sector, and to reach this goal the following activities have been anticipated:

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- Realization of sustainability studies for the retreatment of mining wastes for raw materials recovery;
- Economical evaluation of the potential cases;
- Definition of authorization procedures for retreatment of wastes in a new processing plant or modified existent processing plants;
- Creation of a subsidized market for sub-products of mining wastes through incentives for transport, use, sale and purchase;
- Set up of information and sensibilization campaigns on using products made by mining wastes.

The most recent Italian norm for the management of excavation residues is the **DPR 120/2017**. This rule concerns excavations for civil and construction works, including a procedure for sampling and laboratory analysis of samples, which can be a useful pattern for the case of raw materials recovery from mining residues. The main indications, classified in **Table 6**, are:

- the minimum number of samples is defined by two elements: excavation area and the volume of wastes;
- sampling must be conducted by excavating trenches and drilling dedicated holes;
- the materials with grain size higher than 2 cm should be discarded and all analyses must be conducted on grain size lower than 2 mm.

Table 6. Sampling requirements imposed in Italy by DPR 120/2017 for excavation works

	Excavation area	***Volume of wastes***	***Minimum number of characteristic samples***	***Representativeness of the sample***	***Excavation type and number***
a	≤1000 m^2	≤3000 m^3	1	The whole area	3 trenches, taking samples to be mixed in one
b	≤1000 m^2	3000-6000 m^3	2	1: 0-1 m 2: deeper	3 trenches, taking samples to be mixed in two (different depth)
c	1000-2500 m^2	≤3000 m^3	2	1: zone A 2: zone B	6 trenches, taking samples to be mixed in two (different areas)
d	1000-2500 m^2	3000-6000 m^3	4	1: zone A, 0-1 m 2: zone A, deeper 3: zone B, 0-1m 4: zone B, deeper	6 trenches, taking samples to be mixed in four (different areas and different depth)
e	2500-10000 m^2	>6000 m^3	3 + 1 every 2500 m^2	1: 0-1 m 2: intermediate 3: deeper	At least one drilling hole for 3000 m^3 of wastes
f	>10000 m^2	>6000 m^3	7 + 1 every 5000 m^2	1: 0-1 m 2: intermediate 3: deeper	At least one drilling hole for 3000 m^3 of wastes

Moreover, the **DPR 120/2017** defines the concepts of by-products from excavation wastes and the useful landfill matrices. The useful landfill matrices are the excavation wastes containing less than 20% of anthropic origin materials, and without any toxic material. Therefore, the excavation wastes can be used in two ways:

- refill materials for environmental restoration;
- by-product of the excavation. It means that the wastes can be moved away from the excavation area; however, they must be treated within the industrial standard practices (**Mazzella et al., 2019**). The introduction of by-product for excavation wastes mainly concerns their reuse for realization of asphalt and concrete. On the other hand, the definition can be a good pattern for valorisation of mining residues for critical raw materials recovery in Italy.

Currently, the Geological Survey of Italy (ISPRA) is building a Geological, Mining, Museum and Environmental Database – GeMMA (**Lucarini et al., 2020**), to collect all relevant information about mining wastes from public and private sources and so to define the national situation of the sector, with particular attention to the sustainability of extraction and practices to the potential exploitation of abandoned stockpiles and tailings.

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GeMMA is aimed to become a valuable support tool for the development of specific national and regional policies, specifically oriented towards sustainable production and efficiency use of primary and secondary resources, addressing and targeting the implementation of the circular economy.

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- **France**

In France, extractive industries are regulated according to extracted substances and not according to mine techniques, such as underground or open pit like in numerous other countries.

In nov-2020, the current French mining code (2011) lists the substances which come under the specific legal regime of mines. These substances include in particular[1]: bauxite, fluorite, phosphates and metallic substances such as Fe, Co, Ni, Cr, Mn, V, Ti, Zr, Mo, W, Hf, Re, Cu, Pb, Zn, Cd, Ge, Sn, In, Ce, Sc, REE, Nb, Ta, Hg, Ag, Au, Pt, PGM, Li, Rb, Cs, Ra, Th, U, S, Se, Te, As, Sb, Bi, Be, Ga, Tl. A project to reform the mining code is underway, aiming in particular to bring it into conformity with the Environmental Charter.

Conversely, any mineral or fossil substance that is not qualified by the mining code as a mining substance is considered a quarry substance, which concerns more or less industrial minerals – such as clays, silica, kaolin, quartz, talc, mica, feldspar, andalusite - and construction minerals – aggregates, ornamental and construction rocks. The operation of these sites is governed by the provisions of the Environmental Code applicable to installations classified for protection of the environment.

France transposed the Directive 2006/21/EC on the Management of Wastes from Extractive Industries on «**Arrêté du 19 avril 2010**» and also by updating the pre-existing legislative texts regarding the two substances classification described above. Two main texts and with recent updates (2017) are concerned: «**Arrêté du 22 sept. 1994**» for industrial and construction minerals and «**Décret n° 2010-1394 du 12 nov. 2010**" namely for metallic mines – see details in references.

In parallel under the French Ministry of Environment, consistent national framework was established to manage post-mining activities, namely with the creation of post-mine centres for studies and operations: GEODERIS and DPSM – see links in references. In accordance with article 20 of 2006 EU directive, GEODERIS structure carried out between 2009 and 2012 an inventory of mining sites having waste deposits: waste rocks most of them in rock heap form and processing waste dumps most of them as layered fine-grained (tailings) dams (**Lemiere et al, 2011**).

This inventory made it possible to group past mines and waste stocks by sectors and classify them according to their potential risk: stability risk on one side and environment and human health risk on the other side. Sectors were ranked from least (A[2]) to most impactful (E), in terms of health and environmental risks. From that time closed or abandoned mine sectors classified D and E have been studied deeper through stability, health and environmental studies. The methodology developed is based on the tools defined within the framework of the French policy on polluted sites and soils, in particular on the state interpretation process. A recent paper gives some details on methodology for several member states including France (**Žibret et al., 2020**).

During preliminary field inventory (2009-2012), portable measurements have been carried intensively on metallic mines and completed by laboratory analyses. Mining residue were sampled on surface and sometimes deeper using manual auger and analysed, adapting the list of elements chosen to the context. In general, 2 to 6 elements were analyzed: the substance produced (Ag, Cu, Pb, Sb, Sn, W, Zn, etc.), the elements with potential impact (As, Cd, Hg, etc.) and / or associated with the treatment process implemented (Hg, CN). Later data collection has been larger for sites with potential major impacts but does not include specifically CRM list since driven objective is to manage risks in coherence with 2006 EU Directive and not to evaluate reprocessing option.

[1] Energetic resources are not considered in this chapter.
[2] Not to be confused with 'category A' waste facilities according to 2006 EU directive with potential major risks

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At the moment these metallic mine sites usually concern hazardous extractive waste which are not considered for retreatment evaluation under classical rehabilitation scenario mainly because of non-economically profitable.

Some research work performed at BRGM allowed to define a characterisation methodology and identify some possible case studies for possible retreatment (**Bellenfant et al, 2013**; **Bertrand et al., 2015**). Field work on case study was performed on Pb/Ag[3] and W contexts (**Bodénan et al, 2015**). A pilot scale operation (4 tons) was performed on the Pb/Ag case to concentrate Pb and Ag. And an economic prefeasibility was addressed in comparison to classical scenario; low profitability was confirmed through detailed calculations.

Also, Ga, Ge, In analyses were performed on Pb-Zn-bearing waste to update information on these CRMs often associated to sphalerite minerals. No major concentrations were found at that time on 27 samples.

Active sites in France concern mainly industrial and construction minerals. Subsequent inert extractive wastes are namely considered in terms of reuse on site such as backfilling and environmental restoration. Professional unions technical guides exist to improve practices and reduce waste production in accordance with EU 2006 Directive.

[3] Ag, silver was in the French list of critical materials at that time (COMES)

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- **Greece**

1. Introduction - Legislative framework

The management of mining waste in Greece is covered by the **JMD 39624/2209/E103/2009** in compliance with the Directive 2006/21/EC of 15 March 2006 on the management of waste from extractive industries.

Furthermore, pursuant to Article 22 of Directive 2006/21/EC, the Commission has adopted the following decisions on the characterization of extractive waste:

Commission Decision of 30 April 2009 No 2009/359/EC completing the definition of inert waste in implementation of Article 22 (1) (f) of Directive 2006/21/EC of the European Parliament and the Council concerning the management of waste from extractive industries.

Commission Decision of 30 April 2009 No 2009/360/EC completing the technical requirements for waste characterization laid down by Directive 2006/21/EC of the European Parliament and of the Council on the management of waste from extractive industries.

The criteria and the required data for the characterization of the extractive waste, according to the Directive 2006/21/EC, the JMD 39624/2209/E103, as well as the relevant Decisions 2009/360/EC and 2009/359/EC are described in part 2.

2. Characterization of extractive industry waste

Pursuant to Annex II of JMD 39624/2209/E103 and Directive 2006/21/EC, extractive waste is characterized in such a way as to ensure the long-term physical and chemical stability of the facility and the prevention of serious accidents. The classification of waste includes, if required and depending on the category of the facility, the following information:

1. a description of the expected physical and chemical characteristics of the waste to be deposited both in the short and long term, with particular reference to its stability under atmospheric / meteorological surface conditions, taking into account the type of mineral or minerals to be mined and the nature of the / or overburdens displaced during mining operations,
2. classification of the waste according to their corresponding entry in Decision 2000/532/EC, as in force, taking into account in particular their hazardous characteristics;
3. a description of the chemicals used in the processing of the minerals, as well as their stability;
4. description of the waste disposal method,
5. description of the waste transfer system used.

Furthermore, in accordance with Article 1 (2) of Decision No 2009/360/EC, the characterization of waste covers the following categories of information:

a) background information
b) geological background of deposit to be exploited
c) nature of the waste and its intended handling
d) geotechnical behaviour of the waste
e) geochemical characteristics and behaviour of the waste

The technical specifications for the characterization of the waste are given in the Annex of the Directive 2009/360/EC.

In accordance to JMD 39624/2209/E103, Directive 2006/21/EC and Decision 2009/360/EC on mining waste, the waste must be classified according to their respective entry in Decision 2000/532/EC and amendments, taking into account their dangerous characteristics.

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2.1 Criteria for inert waste

In accordance with Commission Decision 2009/359/EC of 30 April 2009 "completing the definition of inert waste in implementation of Article 22 (1) (f) of Directive 2006/21/EC of the European Parliament and the Council concerning the management of waste from extractive industries", the waste of the extractive industry is considered inert within the meaning of Article 3 (3) of Directive 2006/21/EC if it meets all of the following criteria, both short-term and long-term:

(a) the waste will not undergo significant disintegration or dissolution or any other significant change which could have an adverse effect on the environment or harm human health;
(b) the waste has a maximum content of sulphide sulphur of 0,1 %, or the waste has a maximum content of sulphide sulphur of 1 % and the neutralising potential ratio, defined as the ratio between the neutralising potential and the acid potential, and determined on the basis of a static test prEN 15875 is greater than 3;
(c) the waste does not pose a risk of self-combustion and will not burn;
(d) the content of the waste of substances potentially harmful to the environment and to human health, in particular As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, V and Zn, including in any fine particles alone of the waste, is low enough to pose a negligible risk to humans and the environment in the short and long term. To be considered low enough to pose a negligible risk to humans and the environment, the content of these substances must not exceed the national limit values for areas designated as unpolluted or the relevant national natural background levels; and
(e) the waste is practically free of products used in extraction or processing which could harm the environment or human health.

Regarding criterion (d) it is stated that in Greece to date no limit values have been established for areas that are characterized as non-polluted and no systematic recording and recording of natural background levels has been carried out at national level. To assess this criterion, the waste content of potentially harmful substances for the environment can be compared with the background values in the wider area of the mining activity under consideration.

The legislation on the classification of waste from the extractive industry (JMD 39624/2209/E103, Directive 2006/21/EC, Decision 2009/360/EC) does not specify specific tests that must be performed to determine the geochemical characteristics of the waste. It is nevertheless worth noting that, in order to meet the relevant requirements of Directive 2006/21/EC, the following guidance documents have been developed by the European Committee for Standardization (CEN / TC292, WG8):

- CEN/TR 16365:2012 Characterization of waste. Sampling of waste from extractive industries
- CEN/TR 16376:2012 Characterization of waste. Overall guidance document for characterization of waste from the extractive industries
- CEN/TR 16363:2012 Characterization of waste. Kinetic testing for assessing acid generation potential of sulphidic waste from extractive industries
- CEN/TS 16229:2011 Characterization of waste. Sampling and analysis of weak acid dissociable cyanide discharged into tailings ponds
- EN 15875:2011 Characterization of waste. Static test for determination of acid potential and neutralization potential of sulphidic waste.

Finally, concerning Greece, there are no laws regarding the valorization of extractive waste.

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Europe and transnational

Legislation

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Italy

Legislation

- Decree from the President of the Republic DPR 120/2017. **Regolamento recante la disciplina semplificata della gestione delle terre e rocce da scavo, ai sensi dell'articolo 8 del decreto-legge 12 settembre 2014, n. 133, convertito, con modificazioni, dalla legge 11 novembre 2014, n. 164.**
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France

Legislation

- Extractive waste (mines and quarries) in France: arrêté du 19 avril 2010 relatif à la gestion des déchets des industries extractives
- Mining code, list of substances: Article L111-1 of Ordonnance n° 2011-91 du 20 janvier 2011 portant codification de la partie législative du code minier.
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- MineralInfo: The French portal for non-energy mineral resources **http://www.mineralinfo.fr/**
- GEODERIS: Public Interest Group (GIP) providing French state (central administrations and decentralized services) with assistance and expertise in post-mine matters **https://geoderis.fr/**
- DPSM: Operational post-mine department **https://dpsm.brgm.fr/**

Greece

Legislation

- Act n° JMD 39624/2209/E103/2009 **Incorporation of Directive 2006/21/EC on the management of wastes from extractive industries, given the current status of mining activities in Greece.**

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