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INTRODUCTION

Raw materials associated with extractive industry: an overview

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ABSTRACT

Globalization, growth in consumption levels and emerging economies such as China and India has led to increasing concerns about the availability of specific mineral raw materials. These resources are finite and rapidly depleting; in the meantime, demand continues to increase. This results in the overall increase in the value of mineral raw material and in the subsequent dramatic price spikes and fluctuations. Therefore, resource security is now a priority for governments of developed countries.

The security of supply of the so-called 'critical' raw materials (CRM), with rare earths (REE) has attracted the greatest attention in the press. The "criticality" concept is based on the combination of economic importance and supply risk for the Mineral Raw Materials (MRM). The EU relies on extra European countries for the vast majority of their critical raw materials (CRM) supply, putting manufacturing and industrial activities within the EU at risk and causing high economic dependence on non-EU countries. On the other hand, these factors drive a need for new sources of mineral raw materials, and, on the other, a need for the EU to reduce its reliance on global imports of such materials and to become more independent.

The primary way to exploit MRM is from mining and quarrying, including exploration and development phases; these activities have always produced huge amounts of waste, which has to be managed and monitored also after the ending of the exploitation phase. In 2014, the extractive industry represented the second most important sector in terms of waste quantities produced in the EU-27 (28.1% or 703 million tons) (**Eurostat, 2017**). EW (Extractive waste) is often mono-waste

material, represented by similar minerals and elements present in the original ore deposit that are not completely exploited. It is predicted that 5.9 billion tons of EW waste is stored within the EU (**BRGM, 2001**).

Extractive waste is a material that must be removed either during mining (e.g. top-soil, overburden, waste rock) or during the processing of ores, industrial minerals and rocks, and/or energetic materials (operating residues and tailings) (Fig. 1). In these waste categories, the desired mineral may be present in the ore in minute amount (sometimes > 1%).

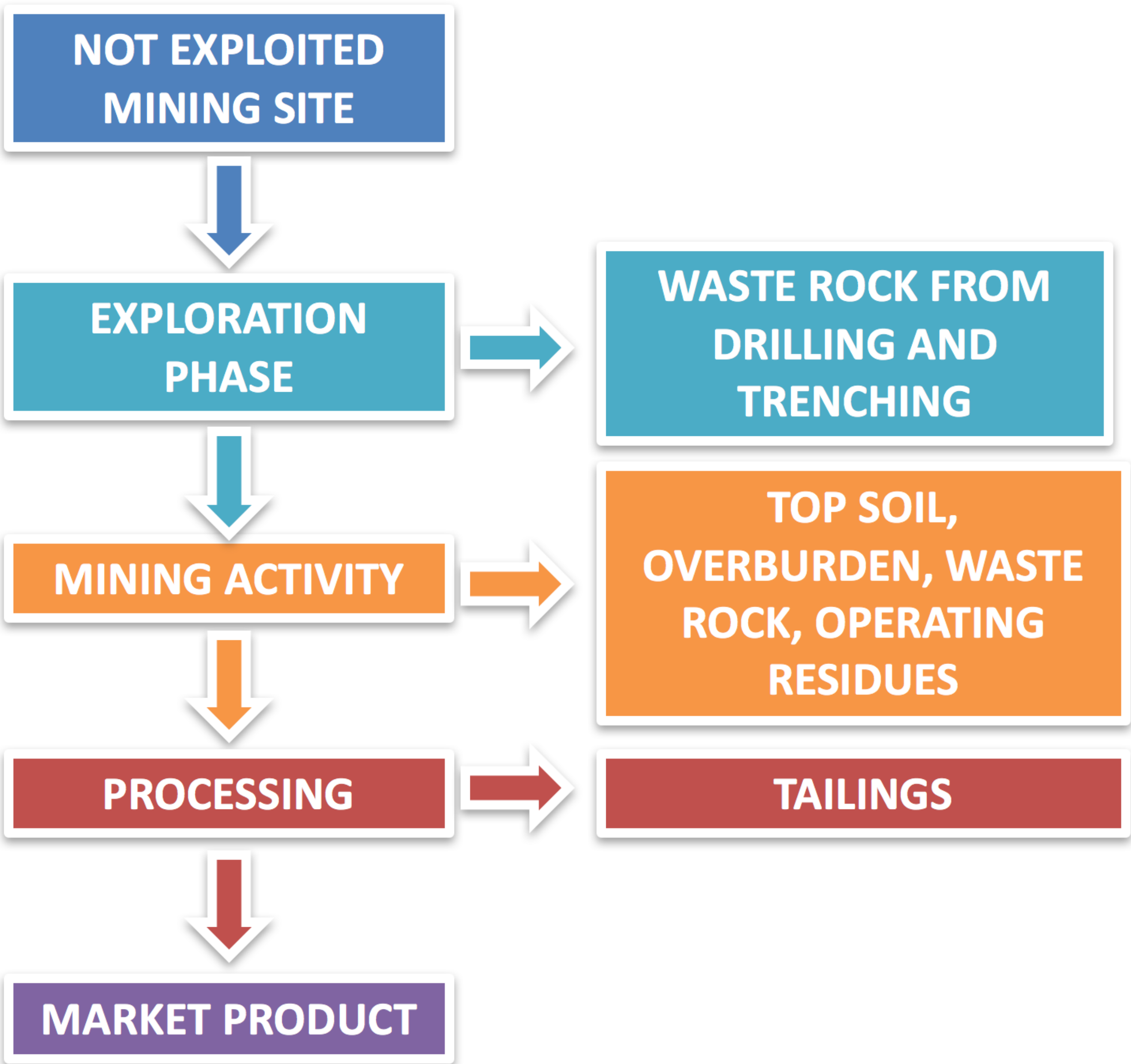

Figure 1: scheme of the different exploitation phases and related waste materials

This Special Issue represents a new and important step in disseminating topics dealing with waste from mining and mineral processing industry within the scientific community. Its goal is to stimulate a debate among geoscientists, about the solutions and techniques, which can be adopted in order to improve the waste management efficiency within the mining and quarrying industry. Extractive waste (EW) presents a serious issue not only on a scientific and political level, but also from the industrial and executive point of view. Both mining engineers and geologists have peculiar knowledge and skills that allow them to study and solve problems pertaining to the management of waste from extractive industry. The Special Issue aims to increase the knowledge of both researchers and professionals working in this field about the practices to be applied on extractive waste management and recovery, in order to help waste producers, recycling plant managers and public organizations.

A point to be discussed relates to the introduction of new instruments aimed to improve the efficiency of data gathering and management (i.e. data connected to waste from exploitation, useful to boost waste recovery). Another topic to be studied is the recovery of waste rock derived from the extractive industry: how can we increase the whole mining yield if not by the improvement of the efficiency in exploiting and processing phases and by carrying out an enhancement of the different wastes (flow waste or that present in landfills and facilities)?

All these recovery and enhancement works should be carried out following the sustainable development principles applied on mining, processing and disposal of mining and mineral processing waste. Exactly for this reason, both studies and experimental tests have to be carried out on laboratory and industrial scale in order to assess the potential use of these materials, which are currently considered as waste but that could become commercial by-products. Some case studies, related to the above-mentioned topics, are also presented in this Special Issue.

1 PROBLEMS AND CHALLENGES CONNECTED TO EXTRACTIVE WASTE MANAGEMENT

1.1 Problems

Over the last few decades, there has been increased interest and emphasis on environmental protection, shaping waste management policies towards an environmental focus and integrated waste management. Some of the waste is inert and therefore does not represent an important threat for the environment and human health. However, it can cause riverbeds to smother or even collapse in case of high quantity storage. The collapse of dams or heaps may have serious impacts on environment and human health and safety. Examples of this are the accidents in Aberfan (Wales, 1966), Stava (Italy, 1985), Aznalcóllar (Spain, 1998), Baia Mare and Baia Borsa (Romania, 2000) and Rio Doce (Brazil, 2015). Other significant impacts can relate to the physical footprints of waste disposal facilities and a resulting loss of land productivity, effects on ecosystems, dust and erosion (**European Commission, 2018)**. Nevertheless, rock waste and tailings deriving from mining activities, mainly connected to metal ore bodies and to dressing plants may contain large amounts of pollutants and hazardous substances such as heavy metals. In many cases, tailings are stored on heaps or in large ponds, thus a potential collapse may have serious consequences on human health and environment. Furthermore, major concerns connected to waste from extractive industries are related to environmental pollution in soil, water, air, transports, lack of landfilling areas, etc. (**Azam et al. 2007; Banks et al., Béjaoui et al., 2016; Fields 2003; González-Corrochano et al. 2014; Helios-Rybicka, 1996; Lim et al. 2009; Mehta et al. 2018; Plante et al. 2015; Schaider et al. 2007; Talavera Mendoza et al. 2016; Tiruta-Barna et al. 2007; Wong 2003; WHO 2015**). These factors can have lasting environmental and socio-economic consequences and be extremely difficult and costly to address through remedial measures. Waste from the extractive industries have therefore to be properly managed in order to mostly ensure the long-term stability of disposal facilities and to prevent or minimize any water and soil pollution arising from acid or alkaline drainage and leaching of heavy metals. That is why the European Union published the Directive on "management of waste from extractive industries", to propose measures to prevent or minimize any adverse effects on the environment arising from the management of waste from extractive industries.

A comprehensive framework for the safe management of waste from extractive industries at EU level is now in place comprising:

- Directive 2006/21/EC on the management of waste from the extractive industries (the mining waste directive).
- Best Available Techniques reference document for the management of tailings and waste-rock in mining activities;
- An amendment of the Seveso II Directive to include in its scope mineral processing of ores and, in particular, tailings ponds or dams used in connection with such mineral processing.

1.2 Challenges

The Waste Management policy aims to avoid the impact of waste on human health and the environment and where appropriate to reduce the natural resource consumption to the maximum. In a 2014 communication, the European Commission (EC) stated that more needs to be done to help reduce the amount of materials sent to landfill throughout their life cycle, by promoting circular economy in support of sustainable growth (**European Commission, 2014)**. It is thus clear that existing and future policies will support a comprehensive approach to waste management, including policy about waste prevention, waste exploitation (RM, SRM, CRM) and contemporary environmental protection.

Extractive waste facilities can represent a vast, untapped resource for valuable materials. Finite resources, including secondary raw materials (SRMs), mineral raw materials (MRMs) and associated critical raw materials (CRMs) such as rare earth metals (REEs) and platinum group elements, (PGEs) are buried amongst waste in mining facilities. These resources are currently sourced from outside of the EU, are under high demand and are becoming increasingly scarce. Thus, EW facilities can be considered as “new ore-bodies”. However, their potential use faces several challenges:

- Establish an approach to exploiting landfills, which is closely linked to the characteristics of the ore body and to the techniques employed for mining exploitation;
- Highlight common problems connected to environmental impacts; indeed water, air and soil impacts depend on the pollutants present in the EW, which can strongly vary depending on the characteristics of the rocks and ore bodies, on the exploitation techniques and on the dressing activities (e.g. cyanides, heavy metals, silica, asbestos);
- Have useful statistics about EW facilities volumes. The official data at EU level (Eurostat) or at Country level report the total estimated volume for EW facilities and for waste stream without specifying the volumes linked to single EW facilities (e.g. EW connected to specific mining activities like Al, Cu, Ni and to dimensional stone – e.g. marble and granites, and also to aggregates). The volume connected to waste stream can be estimated using the national or EU production of main products (e.g. MRM as for mines, slabs as for dimension stones and aggregate production), together with literature data about waste production associated to each mine/quarry category and with data obtained using GIS and aerophotogrammetry for an approximate volume estimation.

2. PAST RESEARCH ABOUT EXTRACTIVE WASTE

The construction stone industry, which is the most voluminous mineral raw material extracted by humans (see **Přikryl et al. 2016; Přikryl 2017**), is characterized by high production of waste material, especially in the case of dimension stone sector (**Gazi et al., 2013**). In particular, the management of the residual sludge (fine size material, produced during working activities, characterized by potential pollution due to heavy metal and TPH content) still represents a problem for companies and society at large. This is due to its high management costs and to the necessity of a proper recovery, alternative to its disposal in dumps, which is a practice no longer compatible with the concept of sustainable development (**Siotto et al., 2008**).

Discussion and studies on the matters related with stone waste can be dated starting from the 1970s (**Careddu and Dino, 2016**). However, the need of a reuse and enhancement of stone waste has been strongly investigated since the 1990s. Special focus has been on silicate waste used as waterproofing material for municipal landfills (**Bertolini and Celsi, 1989**; **Frisa Morandini and Verga, 1990**), feldspar and quartz recovery for use in ceramics and glass industries (**Curreli et al., 1992**; **Sassone and Danasino, 1995**), or making sludge inert applying the same technologies as employed in the ceramics and glass industries (**Pelino et al., 1998; Rincón and Romero, 2010)** This last topic has recently shown good scientific attractiveness.

At the end of the 1990s and in the following years, other potential re-purpose ideas/ techniques were investigated. In particular, several lines of investigation about the reuse of sludge for land reclamation were carried out. Such research is based on the premises required by the law for quarrying activities. A mandatory phase of environmental rehabilitation of both dumps and quarrying areas, as well as properly treated sludge, is required before they could be used as ‘‘new soil’’ for these purposes. Several studies investigate the use of different materials, other than topsoil, to be employed for quarry rehabilitation (**Barrientos et al., 2010**; **Burragato et al., 1999**; **Dino et al., 2014; Dino et al. 2015; Sivrikaya et al., 2014**).

The reuse of carbonate stone waste is surely more viable compared to silicate rock waste. This is due to the widespread use of $CaCO_3$ in many industrial applications, not only in construction but also in other important sectors such as environmental, food, pharmaceutical, paper, etc. (**Careddu and Marras, 2015**). However, state of the art in recovery and utilization of calcareous rock is typically to replace more expensive building materials; this kind of aggregates comes especially from non-economic blocks and rubble crushing.

Another problem has to do with scraps coming from block sawing at the stone-processing plants; this is because the sawdust is regarded as less important when compared with the crushed calcareous aggregate produced in stone processing plants. Laboratory tests of limestone microfines have ruled out the presence of polluting substances. (**Careddu et al., 2014**). Still, however, dewatered sludge can be a problem. References about the reuse of fine dust resulting from the processing of marble mainly pertains to products such as: concrete (**Almeida et al., 2007**; **André et al., 2014**; **Felekoglu, 2007**; **Gencel et al., 2012**; **Marras et al., 2010b**; **Rana et al., 2016; Topçu et al., 2009**), cement plaster (**Marras et al., 2017**), ceramic (**Devant et al., 2011; Díaz and Torrecillas, 2007**; **Marras et al., 2010a**; **Montero et al., 2009a,b**; **Saboya et al., 2007**), and other building products (**Galetakis et al., 2012**;**Lee et al., 2008**). Other limestone sawdust used in the acid mine drainage (**Barros et al., 2009**). **Sort and Alcañiz (1996)** studied the effects of sewage sludge additions to control erosion in limestone quarries.

As for the mining industry, there has been a number of studies about the use of waste rock or tailings by construction developers (**Ahmari and Zhang, 2012; Castro-Gomes et al., 2012; Cullu and Ertas, 2016; Liu, et al., 2016; Yellishetty et al. 2008**). Others investigated the recovery to make industrial minerals (**Bozzola et al., 2010),** metals **(Carranza et al., 2016; Gordon, 2002)** and CRM **(**e.g. REE from Pb- Zn mine tailings; **Medas et al. 2013**) usage. EW have been also investigated to be used for plantation or revegetation around the site, by using it as soil additive **(Nouri et al. 2011; Zou et al. 2012)**.

3 OVERVIEW OF THE RESEARCH SELECTED FOR THE SPECIAL ISSUE

Sessions on extractive industries waste management and recovery at the European Geosciences Union (EGU) General Assembly in 2017 have fostered a debate and editorial initiative on these themes, stimulating geoscientists to show and share their research. This volume aims to take this debate forward. The content is certainly not complete because of the enormous breadth of types of waste and diversity of the localities where the ore deposits are naturally located (i.e. differences in the environment, ecosystem, social matters, countries, etc.). Nevertheless, it represents an invitation for dialogue, reflection and analysis of some extractive waste issues for which both geoscientists and stakeholders are called to give answers.

The papers are grouped into two sessions: 1) Mining and Mineral Processing Waste Management and Recovery; 2) Stone Waste Management and Recovery.

The first section focuses on mining and mineral processing waste management related to various aspects of management and recovery. In particular, **Benarchid et al. (2018)** investigate the recycling potential of gold mining waste rocks as construction materials according to Quebec (Canada) recycling guidelines of non-hazardous inorganic wastes and scientific point of view. Considering the measured technological and environmental properties, concretes with good mechanical performance could be manufactured.

Dino et al. (2018a) stress that extractive waste can surely help in secondary raw material and critical raw material supply: fundamental is the characterization of the waste site and of the extractive waste present in the potential "new ore body" to exploit (sampling phase, physical-geochemical-mineralogical characterization, volume estimation, etc.). Starting from a case study in North Italy, a potential economic viability of landfill mining has been assessed.

Markovaara-Koivisto et al. (2018) focus on an interesting case history from Finland showing the importance of evaluating the use of proper methodologies to study the volume and concentration of extractive waste present in a closed extractive waste facility (a tailings pond). Geophysical investigation and field survey have been carried out.

Dino et al. (2018b) evidence the importance to study the challenges of potential recovery of extractive waste, applying an interdisciplinary approach (REEP approach). This includes resource efficiency (extractive waste exploitation) and environmental protection (risks associated with extractive waste facilities). This approach can help those decision makers who are interested in extractive waste management and potential recovery. Two Italian case studies are presented.

Health and safety aspects have been investigated in **Baietto and Marini (2018).** In order to excavate greenstones (serpentinite rocks) and waste rock reuse, knowledge on asbestos presence is mandatory. A methodology for the determination of asbestos concentration has been provided and validated.

The second section brings a collection of articles dealing with waste coming from the Dimension Stone industry and other quarrying activities. **Gautam et al. (2018)** use a limestone quarry waste in open graded friction course (OFC). The study suggests that a portion of 25% of re-managed limestone aggregates can be used as partial replacement of conventional aggregates in OGFC for low volume roads, parking, and footpaths.

Marras and Careddu (2017) deal with an environmentally attractive reuse of the marble sludge, recovered from marble sawing and slurry processing. The study is carried out in order to link this by-product to the tire industry. The data emerging from the tests demonstrate that it is possible to identify a way to use marble sludge as a filler in high added value products and, at the same time, how environmental burdens produced by the stone-processing industry could be reduced to much lower levels.

Cavallo (2018) investigates the characterization, the potential reuse and the critical issues connected to serpentinite waste materials. The research focuses on Valmalenco (central Alps, northern Italy) materials. A detailed mineralogical, chemical, physical and microstructural characterization of waste materials was carried out. The preliminary results suggest interesting applications in the ceramic industry, as well as alternative uses as a filler for plastic and rubber materials, up to carbon dioxide sequestration. Special care must be taken to avoid chrysotile asbestos contamination.

Finally, **Rigopoulos et al. (2018)** focuses on a safe method for carbon capture and storage (CCS) using mining carbonation. Mafic lithology seems to be among the most promising rocks for mineral carbonation due to their high content in Ca, Fe and Mg-bearing silicate minerals, which react with CO_2 to form stable carbonate phases. The research stresses the potential use of waste material from mafic rock quarries for CCS, following the ball milling process. Other potential applications include the use of ball-milled mafic rock quarry fines (i) as feedstock for ex situ mineral carbonation, and (ii) as nano-additives in replacement to the binder, for the production of environmentally-friendly building materials which may be able to sequester CO_2. Both applications could substantially contribute to the mitigation of atmospheric CO_2 concentrations over the next few decades, as well as to the upturn of the quarrying industry.

4 CONCLUSIONS AND FUTURE PERSPECTIVE

The European mining and quarrying industry plays a fundamental and inevitable role in the development of society, supplying indispensable materials and managing valuable resources. Yet, however, during the last decades the industry has more often become associated with environmental challenges following the exploitation of the resources. Most of recent European legislation and advocacy by e.g. environmentalists have brought about a generally negative attitude towards the mining sector and EW facilities in general.

The common thought has been that mining and processing aim to exploit finite natural resources, guaranteeing earnings for the mining companies, but at the same time causing potentially negative environmental and social impacts. Another common attitude of most Europeans is that mineral raw materials that are needed in contemporary society can be extracted elsewhere expect our backyard (that is to say European), most desirably in less developed extra European areas. Reference is sometimes given to developing countries, where the human rights and salaries may not be guaranteed. But it is also possible to evidence the positive impact of mining activity for the society due to the fundamental need of raw materials and critical raw materials in a developed society (**International Council of Mining and Metals (ICMM), 2012**) and development of new technologies directly associated with 'in region' exploited materials. Mining also generates new jobs **Trigger, 2003**), taxes and royalties, that are often spent for the benefit of citizens (**Auty and Warhurst, 1993; Mikesell, 1994**) and to maintain vital communities in the mining areas.

Like any industry, mining and quarrying should be performed in a sustainable way. Mining is the exploitation of non-renewable resources, a real challenge for the whole idea of sustainability. Sustainability in this case refers to a production, which is in an optimum balance between the geological resources and the various kinds of physical and societal surroundings (**Danielsen & Ørbog 2000; Danielsen & Kuznetsova 2016; Přikryl et al. 2016).** Any encroach upon nature should give a maximum of added value to society, without causing a need for re-deposition or pollution, or being in conflict with the Construction Products Directive (CPD). The mining industry must specifically decide its actions in order to be sustainable.

From the beginning of the century, something changed at global level and more and more the term "sustainable mining" started to disseminate (**Kirsch, 2009; Whitmore, 2006; Young and Septoff, 2002; Přikryl et al. 2016**), and mining started to work for the decrement of costs and risks connected to environmental and social impacts (**Esteve, 2008; Hamann, 2003; Van Berkel, 2007a, b**). In 2001, the International Council of Mining and Metals (ICMM) was constituted and in 2002 started the Mining, Metals and Sustainable Development (MMSD) project, which acted as triggers for mining industry to reconsider their policy in a more "sustainable" way, embracing the sustainability agenda (**International Council of Mining and Metals (ICMM), 2012; International Institute for Environment and Development, 2002**).

Nowadays, thanks to modern technologies and new instruments (e.g. cost / benefit analysis - CBA, life cycle assessment - LCA, Sustainability reporting, etc.) mine exploitation and, mainly, EW management can be arranged in order to exploit RM and SRM (for industrial markets other than the main one) and to reduce (or avoid?) negative impact on the environment and on human health.

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