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Editorial

Editorial for Special Issue "Pollutants in Acid Mine Drainage"

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Acid mine drainage (AMD) is among the major environmental concerns related to mining activity and often causes the complete degradation of affected ecosystems during and/or after mine closure. AMD is a particular research focus owing to its incorporation of assessments of various pollutants' presence, reactivity, and biogeochemical behavior [1,2]. Additionally, the properties of these polluted mine waters constrain the efficacy of monitoring plans and the environmental remediation approaches.

The systems affected by AMD have high heterogeneity and generate samples with complex matrices [3]. Moreover, AMD frequently creates high amounts of colloids [4], typically in the nanoscale dimensions [5]. Further, this mine drainage represents peculiar ecosystems dominated by acidophilic organisms involved in complex interactions that influence the migration and fate of pollutants [6–9]. In addition, the evolution of AMD promotes the development of new mineral phases that control the concentration of contaminants and seasonal behavior of the affected systems [10,11].

Extensive literature exists about the origin of AMD in relation to the oxidative dissolution of sulfide minerals [12–14]. Nevertheless, the complexity of biogeochemical processes involving the diversity of minerals and cyclic reactions with acidophilic microorganisms continue to be interesting research topics. Also, the state of the art refers to several works dealing with properties, environmental impacts, and treatment processes (e.g., [2,3,15,16]). However, in these peculiar waters, pollutants' diversity, mobility, and geochemical behavior are very site-dependent. The paragenesis of each ore deposit, climate, and engineering options of exploitation and waste deposition (among many other factors) controls the nature and degree of pollution. Moreover, the importance of natural attenuation processes and monitoring efficiency depend on the geology (sensu lato), hydrology, and deposition structures, like waste piles and tailing dams. Important research efforts have been undertaken in the laboratory and field to increase knowledge about the behavior of these complex, affected systems [17].

In light of these considerations, this Special Issue addresses a wide variety of topics, such as the source and nature of pollutants, speciation, mobilization/precipitation, and toxicity of trace elements. Additionally, the articles featured in this publication cover the modeling of processes, innovative techniques for removal of hazardous elements, and advanced monitoring techniques, aiming to enlarge the base knowledge about pollutants in AMD. Therefore, the published papers present the latest advances in (bio)geochemistry and mineralogy of AMD and wastes from which AMD develops. The Special Issue contains 19 articles that provide examples of methodological approaches and novel tools and solutions for the monitoring, treatment, and remediation of AMD.

Geochemical modeling is an important research focus in this Special Issue [18–22]. This relevance is emphasized by Nordstrom's work [18], which showed the role of these models in understanding aspects such as speciation and natural attenuation, while exploring treatment processes for the recovery of metals in these complex matrices. In different geological contexts, Drapeau et al. [19] and Skierszkan et al. [20] also presented geochemical modeling to investigate the mobilization of lead and uranium, respectively. Geochemistry and mineralogy were used by Lemos et al. [21] to determine the AMD potential and establish the

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ability to mobilize potentially toxic elements (PTE), even in alkaline conditions. The authors highlighted the importance of using geochemical experiments to support sustainable tailings management. Combining geochemical modeling with acid–base neutralizing capacity (ANC–BNC) tests, Drapeau et al. [22] proposed an approach for characterizing siliceous and calcareous mining wastes and modeling pH evolution, and advocated element mobility as a function of the added amount of acid or base. However, with regard to the topic of modeling, Raymond et al. [23] focused on the behavior of waste rock cover systems and used a numerical model for understanding metal release as a function of water infiltration. In the domain of previewing the AMD potential, Moyo et al. [24] investigated the uncertainties associated with standard static tests and the importance of sulfur speciation when calculating potential acidity. The impact of the oxidation state of sulfur on the mobility of metals in contaminated sediments was investigated by Langman et al. [25]. The authors concluded that adding algal detritus to Fe- and S-rich sediments in a mining-impacted lake enhances Mn release but may not affect other toxic elements (e.g., As, Cd). Ódri et al. [26] investigated how the degree of isotope fractionation could help to understand the release and transport of pollutants in AMD.

The articles by Pi-Puig et al. [27], Menshikova et al. [28], and Kim [29] focused on the secondary minerals formed in a diversity of geological and climate scenarios. Pi-Puig et al. [27] proposed a genetic model for crusts and efflorescence and highlighted their roles as sources of contamination during the wet season. Menshikova et al. [28] characterized the secondary precipitates, emphasizing the amorphous phases formed under the influence of mine waters. Kim [29] demonstrated the natural attenuation potential of iron and Mn oxyhydroxides, which are able to retain toxicity mobilized from wastes with pyrite and manganese pyroxene.

The papers by Zawierucha et al. [30], Kato et al. [31], Ryskie et al. [32], and Santos et al. [33] were related to diverse processes and tools for the treatment of AMD. Zawierucha et al. [30] showed a novel approach based on the selectivity of elements of environmental concern, especially arsenic. The technique consisted of applying polymer inclusion membranes (PIMs) and revealed an efficiency of 90% in the removal of arsenic. Passive treatment through wetlands was considered by Kato et al. [31]. The authors modeled the mechanisms of pollutant removal by incorporating reactions into GETFLOWS. The results were consistent with adsorption on ferrihydrite observed in analyzed sediment samples. Ryskie et al. [32] presented a review of contaminants of emergent concern (CEC) in mine water and cold climates, e.g., rare earth elements, cyanide, and nitrogen compounds. The authors began by clarifying the definitions of this concept and continued reviewing the treatment strategies based on the best available technologies that are still economically viable.

Santos et al. analyzed microalgae's role in remediation [33], showing the use of algal growth for biosorption processes. The *Scenedesmus* genera revealed the ability to improve AMD quality and reduce pollutants toxicity. Algae were also analyzed in the study of Gomes et al. [34], exposing the stressful ecological conditions of AMD. The association between the algal community and hydrological patterns, obtained from digital surface models and flow maps of toxic elements, was presented as a relevant tool for biomonitoring AMD systems. In the same metallogenetic context (Iberian Pyrite Belt—IPB, SW Europe), there was the paradigmatic Rio Tinto, presented in the research of Olías et al. [35], which also showed the extreme conditions of AMD. The authors analyzed the evolution of pollutants concentrations and loads, highlighting the control by rainfall and concluding with the expected long-term persistence of pollutants mobilization in this river system. Still, in the IPB, the work by Flores et al. [36] presented a methodological approach to monitoring. They applied high-resolution unmanned aerial system (UAS)-based hyperspectral mapping and machine learning tools to detect geochemical and mineralogical variations and then related them with concentrations and physicochemical properties in the river system.

The above-presented works showed AMD to be a global problem worthy of investigation with manifestations worldwide. The diversity of addressed subjects illustrated the magnitude of this environmental problem and the recent evolution of knowledge about pollutants in AMD. Moreover, it contributed to new approaches to and techniques for AMD monitoring, modeling, and remediation.

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