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Geoenvironmental characterization of unstable abandoned mine tailings combining geophysical and geochemical methods (Cartagena-La Union district, Spain)

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A B S T R A C T

This study presents the results of the geoenvironmental characterization of the Brunita mine pond in the Cartagena-La Unión mining district, Murcia (SE Spain). The main objective was to evaluate the present conditions of the mine tailings in order to identify related environmental hazards. Since 1956, the Brunita mine tailings were being stored in four stepped ponds at the watercourse of a NNO-SSE trending ravine. Subsequently, they were stored in a single, large pond. After the closure of the pond operations, certain work on dike stabilization was performed and debris from the Brunita mine started to accumulate. The mining works for > 50 years have led to the complete burial of the surrounding valleys and hills by mine waste material. Electrical resistivity tomography (ERT) has allowed the determining of both the general geometry of the pond base and the thickness of the mine tailings. Surveys along a total of 6 ERT profiles, 3 longitudinal and 3 transverse profiles to the largest dimension of the pond were carried out. The strong resistivity contrast between the infilling and the bedrock is high enough to clearly define the bottom pond boundary. Low resistivity values (< 10 Ω·m) characterize the infilling of the pond, whereas resistivity values > 200 Ω·m correspond to the Paleozoic rocks that constitute the base of the deposit. Vertical steps have been recognized defining strong variations in the thickness of the deposit. This geometry results from the interaction between the paleotopography of the previous valley and the different growth stages of the deposit. The depth of the pond's base obtained from two boreholes has confirmed the results obtained from ERT profiles. Significant amounts of pyrite and siderite and an appreciable presence of sphalerite and galena were determined by XRD of representative samples. Accordingly, high contents of toxic metals (Cd, Cu, Pb, Sn and Zn) and As were detected in chemical analyses, which show the potential of the tailings to release substantial amounts of these pollutants into the surrounding soils and watercourses. AMD has been identified and percolation through the base of the pond could occur at its northeast sector, where a low resistivity area is recognized. The manifest instability of the tailings pond makes it necessary to include physical stabilization in remediation and monitoring in order to minimize the environmental impact of the tailings on the areas affected, which is located in one of the most popular tourist areas in SE Spain.

1. Introduction

There are almost eighty mineral waste structures, resulting from mineral exploitation activities over the last century, distributed throughout the entire region of Murcia (especially in the Cartagena-La Unión district) in the southeast of Spain (Robles-Arenas et al., 2006). The Cartagena-La Unión mining district is one of the most notable places of geochemical pollution and geotechnical instability in Spain's abandoned mining heritage (IGME, 2002; Rodríguez et al., 2011). The Brunita mine pond is one of the numerous tailings deposits in the

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district, affecting the surrounding watercourses that reach La Manga coastline, a major tourism location in SE Spain (Robles-Arenas et al., 2006). Agricultural soils, groundwater, flora, fauna and human beings are negatively affected (Robles-Arenas et al., 2006; Martín-Crespo et al., 2012).

The Spanish Ministry of the Economy, through the Directorate General of Energy Policy and Mining, has prepared an inventory of the abandoned mine waste deposits (IGME, 2002). A relevant contribution of this inventory consists in the definition of a classification of the existing mine waste deposits based on their hazard potential for the human population and infrastructure. The inventory also provides a qualitative geotechnical and environmental assessment of the elements at risk and an associated description. Due to the preliminary nature of the inventory, which was carried out by means of visual surveys and without sampling or testing, further knowledge is required of the current status of the identified deposits with the highest potential risk.

This work presents the results obtained by the joint application of geophysical, mineralogical and geochemical techniques to study the Brunita mine pond (Cartagena-La Unión district).

A shallow, non-destructive geophysical technique (electrical resistivity tomography, ERT) was used to delineate the mine pond geometry and thickness of the infilling, possible existence of interior water flow and the occurrence of acid mine drainage leaks. Regarding the application of electrical and electromagnetic techniques for the characterization of mine waste deposits and related contamination, good examples can be found in Buselli et al. (1998) and Campbell and Fitterman (2000). The ERT technique has mainly been used on waste piles (Painter et al., 2000; Yuval and Oldenburg, 1996) and tailings dams (Niederleithinger and Kruschwitz, 2005; Sjodahl et al., 2005), whereas very few studies have focused on the internal structure of mine tailings ponds (e.g. Kuras et al., 2008; Martínez-Pagán et al., 2009; Gómez-Ortiz et al., 2010; Martín-Crespo et al., 2010). Different electrode arrays are possible, with different horizontal and vertical resolutions, penetration depths and signal-to-noise ratios (e.g. Sasaki, 1992; Szalai et al., 2009). In order to combine a good penetration depth, reasonable vertical and horizontal resolution and a good signal-to-noise ratio, the Wenner-Schlumberger array was chosen for this study. This array has been successfully used in similar studies (e.g. Martínez-Pagán et al., 2009; Gómez-Ortiz et al., 2010).

A significant contrast in resistivity normally exists between the bedrock of the mine pond base and their infilling material (Martín-Crespo et al., 2010). This fact enabled application of the ERT results to define the depth and geometry of the bottom boundary and, consequently, the geometry and thickness of the infilling material. Other features such as preferential flow paths, fissures and faults were also detected using the electrical resistivity method.

We applied mineralogical and geochemical characterization techniques (X-ray diffraction, ICP-MS and AA). Several aerial photographs at different times were also used to evaluate the changes in relief that have progressively occurred due to the accumulation of tailings, and to contrast the information provided by the electrical resistivity tomography.

These studies allow an analysis and quantitative assessment of the structural stability and pollution risk (Painter et al., 2000; Martín-Crespo et al., 2010; Martín-Crespo et al., 2012; Martín-Crespo et al., 2015). They are also essential for prevention of fatal hazardous events, such as the one that occurred in 1972 at this mine pond (Rodríguez et al., 2011; Mouzo Pagán, 2012), or environmental disasters such as the one in 1998 at the Aznalcóllar mine pond, in Seville (Aguilar et al., 2004, 2007).

2. Study site

The Brunita mine pond is located to the south of the town of La Unión (SE Spain) (Fig. 1a). Its maximum dimensions are 410 m × 235 m, with a surface area of 96,000 m^2. The mine tailings are flotation deposits of medium-to-fine-grained, sand-size material. They were produced from grinding and metallurgical processing of pyrite, sphalerite and galena from the Eloy and Brunite mines, by works carried out between 1952 and 1981 (Villar et al., 1991; IGME, 2002). The main ore minerals are pyrite, sphalerite, galena, marcasite and pyrrhotite. Other minor sulphides include chalcopyrite, minerals of the tetrahedrite-tenantite group, arsenopyrite and stannite. Gangue minerals include chalcedony, quartz, siderite and greenalite (López García, 1985; Sanmartí et al., 2013).

The tailings were piled up on Paleozoic graphitic schists and quartzites from the so-called "Complejo Nevado-Filábride" of the Betic Cordillera and upon limestone and phyllites from the "Complejo Alpujárride" that discordantly overlies the Paleozoic rocks (Fig. 1b).

The region is characterized by a semiarid Mediterranean climate with dry summers and mild winters (Martín-Rosales et al., 2007; Robles-Arenas and Candela, 2010). According to data collected by the closest and most complete automatic weather station of the Agricultural Information System of Murcia (La Aljorra, 2000–2016 period; SIAM, 2017), the mean annual temperature was 18 °C, with a minimum in January (− 2 °C) and a maximum in July (41 °C). Rainfall was extremely variable, with intense storms in October and September (maximum rainfall event in a 24 h period of 163 mm). Due to the low precipitation (annual average of 279 mm) and high evapotranspiration (annual average from tge Penman-Monteith method of 1368 mm) only ephemeral streams that drain into the Mar Menor coastal lagoon during heavy rainfalls exist. In October 1972, an extremely intense rainfall event caused instability in the Brunita mine pond (Rodríguez et al., 2011; Mouzo Pagán, 2012). A flash flood of the tailings killed one person and caused serious material damage. As a result, a riprap was constructed as a retaining wall of the coarse-grained tailings. Since 1981, when the mine was closed, no further works on restoration or reclamation have been carried out.

3. Methodology

3.1. Analysis of the evolution of the mine pond morphology

The evolution over time of the morphology of the Brunita mine pond has been determined from the analysis of aerial photographs in the following years: 1929 (photogrammetric flight by Ruiz de Alda); 1946 and 1956 (flights by the Geographic Service of the Spanish Army); 1973, 1981, 2004 and 2013 (flights by the Spanish National Geographic Institute). To better distinguish the changes related to the natural land processes from the anthropogenic changes, we worked with anaglyphs of orthoimages from years 1946, 1956, 1981 and 2004 (Cartography Service of the Murcia Region, http://cartomur.imida.es). The images were georeferenced in a GIS for mapping of the main morphologic elements.

3.2. Description of sampling

Non-disturbed rock drill core samples were collected from a borehole (BH 2) using a TP-50/400 rotary drill with a minimum core bit diameter of 100 mm, up to a sampling depth of 24 m in the Brunita mine pond (Fig. 1a, 2). The sampling was sequential with a constant vertical spacing of 1 m. It was carried out by digging below the surface and casting aside the parts corresponding to surficial sealing to prevent wall material from falling during drilling. Following this procedure, 25 unaltered samples were collected from 0 to 24 m in depth. The samples were air-dried for 7 days, passed through a 2-mm sieve, homogenized, and stored in plastic bags at room temperature prior to laboratory analysis. During the field survey carried out in March, the mine pond was flooded in its northernmost part and the water table located at a maximum depth of 0.5 m. A water sample from the pond was collected (Fig. 2a) in a 250 ml plastic bottle, kept in a refrigerator at 4 °C, and filtered with 45 μm pore spacing, prior to sending it for analysis. In