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Influence of measurement conditions on the resolution of electrical resistivity imaging: The example of abandoned mining dams in the La Carolina District (Southern Spain)

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ABSTRACT

The La Carolina district, which is located in Jaen (Southern Spain), has experienced important mining activity for centuries. These long-standing mining activities, which have been associated with the presence of a philonian network of metallic sulfides, have generated vast accumulations of mine wastes—primarily tailings impoundments—that contain high levels of heavy metals from ore concentration plants. In this paper, the resolution of electrical resistivity imaging (ERI) is analyzed to determine the internal structure of these tailings dams and to assess the influence of the tailings over groundwater and surface water. The "La Manzana" dam, which is one of the largest sludge dams in the district, was selected to achieve this objective.

First, old aerial photographs that were taken prior to the existence of the tailings dam were examined. Second, probing was performed using mechanical drilling, which enabled the identification of the features of the fill material, the thicknesses of the mine tailings and the contact zone between the mining structure and the basement. Third, the probe acts as a piezometer, which is an excellent tool to correlate the geophysical prospecting techniques. The characterization of the internal geometry of this structure has been performed by two ERI surveys, in which electric profiles were obtained under different moisture conditions. During the dry season, this methodology has been effective for identifying the morphology of the structures, contact with the substratum, variations in the vertical and horizontal distribution of the deposited material, and the fracture zones, as well as the contact between the tailings and the substratum on which they are deposited. Conversely, during the wet season, this contact was not distinct in the profile; however, variations in the saturation degree of these deposits, preferential infiltration areas and water flow through the interior of the tailings dam were observed. Last, the ERI survey confirmed the absence of waterproofing measures in the dump areas, which represents a high risk of soil and water pollution in the surrounding areas.

1. Introduction

The metallogenic district of La Carolina (Southern Spain, Jaen province, Fig. 1) is characterized by the presence of vein deposits, which are primarily composed of galena (PbS). These mineral deposits were intensely exploited, and the mine was abandoned at the end of the 1970s. For centuries, the abundance of these deposits facilitated the development of important underground mining activities. This activity produced a substantial amount of waste rock, which was deposited near the mining exploitation site (Gutierrez-Guzmán, 2007; Contreras and Dueñas, 2010). Concurrently, a mineral industry was developed via the creation of numerous gravimetric and flotation washing sites. This industrial activity generated fine-sized and medium-sized wastes that were deposited in spoil heaps and impoundments, which occupied relatively extensive areas in the vicinity of the concentration plants; no remediation was performed.

Sulfides present in the gangues are unstable under the oxidizing conditions to which they are exposed. Their presence will produce negative consequences for the environment because leachates with high concentrations of sulfates and metallic elements are produced in this sector (Hidalgo et al., 2006, 2010) and other regions with similar problems (Sobanska et al., 2000; Li and Thornton, 2001; Chopin and Aloway, 2007). These environmental concerns emphasize the need to determine the geometry and internal structure of this mine waste. This study employed direct techniques to extract a continuous core sample by rotating mechanical drilling, combined with indirect geophysical prospecting techniques, particularly electrical resistivity imaging (ERI). The latter methodology has been used in nearby areas (Martínez et al., 2012; Rey et al., 2013), where it has proved to be useful

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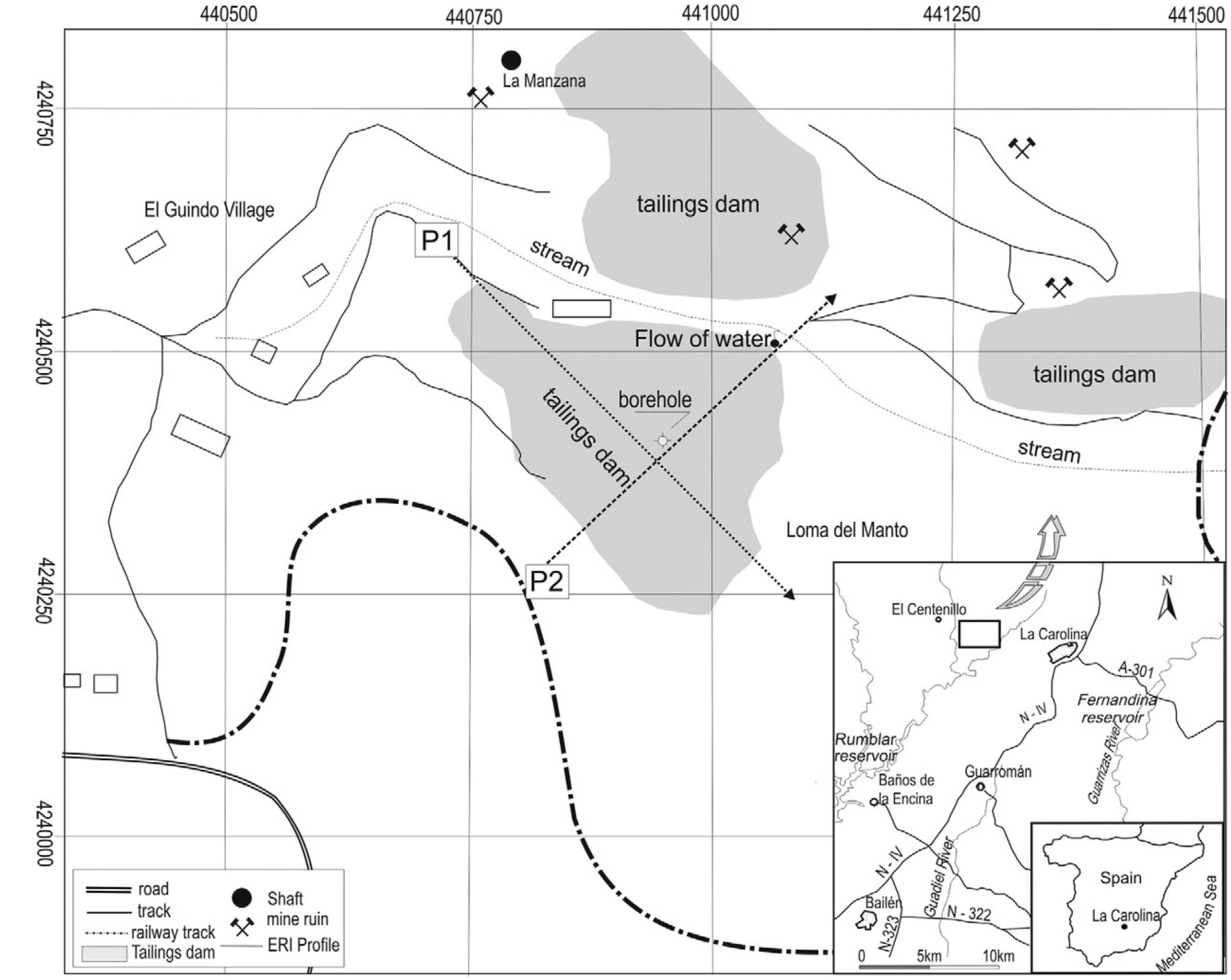

Fig. 1. Location of the study region and the positions of the borehole and ERI profiles (P.1 and P.2).

for characterizing the morphology of the tailings dams, locating recharge–discharge zones and identifying the contact between the residue and the substratum on which it is deposited.

This paper also analyzed the effectiveness of this geophysical technique under different environmental conditions. Profiles were obtained at the end of the rainy season (at the end of March) and at the end of the dry season (September) to compare the results. In addition to serving as a piezometer, the drilling performed in the tailings dam facilitated the analysis of the correlation between the lithology and the resistivity values.

2. Geological setting

The mining district of La Carolina is located on the southeast slope of Sierra Morena within the southeastern boundary of the Hesperian Massif (Julivert et al., 1972; Tamain, 1972). From a regional perspective, two large groups of materials can be distinguished: Paleozoic bedrock and a post-Hercynian sedimentary cover (Fig. 1).

The Paleozoic basement is formed by a succession of metasedimentary rocks (predominantly phyllites and quartzites) that range from Ordovician to Carboniferous in age (Ríos, 1977; Fontboté, 1982; Lillo, 1992). However, the distinguishing feature of the district is the presence of a granitic massif that intruded at the end of the Hercynian Orogeny (Castelló et al., 1976).

The post-Hercynian sedimentary cover fossilizes the mineralization and discordantly overlies the bedrock in a subhorizontal orientation. It is exclusively formed by Triassic, Miocene and Quaternary materials.

The origin of the dike network in La Carolina is associated with the extensional conditions and the anomalous geothermal gradient that existed at the end of the Hercynian Orogeny. These mineralizations have a hydrothermal origin that is associated with the percolation of the fluid phase and metals through fractures and discontinuities of the granitic mass and the Paleozoic host rock. These hydrothermal veins, which are primarily composed of galena, sphalerite, chalcopyrite, pyrite, quartz, ankerite and calcite, are hosted by the Paleozoic bedrock and the granitic body (Lillo, 1992).

3. Materials and methods

3.1. Description of the study area

One of the largest tailings dams in the area was selected (La Manzana) for this paper. The mining waste deposited here was generated during the concentration process of galena by gravity and flotation. In this sector (Fig. 1), the veins hosted in phyllites justify the pelitic nature of the residue. The dimensions and volume of the dam are $250 \times 400 \times 20$ m and 2,000,000 m^3 of mining wastes, respectively (Fig. 2A). The dam is located in a basin in which two streams converge; the runoff waters are channeled by a pipe at the bottom of the deposit. The structure was constructed from a small dam that is composed of factory loose materials by upstream water swelling. The tailings were deposited by a gravity waste system on the edge. The drainage was carried by an existing side chimney drain and pipes connected to the bottom pipe. A spring with a constant flow rate of 2 L/s throughout the year,