Evolution of mine water uses in the abandoned sulphide mines of the province of Jaén, Spain

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Abstract The district of Linares-La Carolina (Spain) includes several flooded inactive sulphide deep mines which are now responsible of the storage and transmission of groundwater in a complex of metamorphic rocks and granitoids of basically impervious behaviour. The existence of natural neutralization processes give as a result net alkaline mine waters in most of the mines, which offer a range of contents in dissolved metals, but acidic drainage is also found in some adits. As surface waters are scarce and there are not aquifers in the area, mine waters have been of interest for agriculture and recreation despite their metal contents.

Key Words abandoned sulphide mines, water uses, South Spain

Introduction

The Linares-La Carolina mining district (province of Jaén) is located in South Spain and includes several inactive sulphide deep mines. The metallic sulphides (mainly galena) in dykes are the reason of the past importance of the region. Exploitation of the ores by underground mining has been an important activity in the area since Roman times or even earlier but abandoned at present. The galena extraction was at its peak around the beginning of the 20th century and this district became the world´s first producer with nearly 65,000 tons of Pb per year (Gutiérrez-Guzmán 2007). Frequent groundwater intakes to the underground workings have been reported along the history of the mining district. This explains that the above mentioned boosting in galena production was associated to the implementation of efficient mine dewatering schemes, first by mean of steam engines and then by explosion and electrical pumps.

The ore genesis of the Linares-La Carolina mining district was associated to the dyke generation following a distensive episode during the late Hercynian orogeny. The Palaeozoic basement is constituted of an Ordovician to Carboniferous succession of metasediment rocks (Rey & Hidalgo 2004; Rey et al 2005). The dominant feature of the district is a granitoid massif – emplaced at the end of the Hercynian orogenic cycle- that intruded through highly folded Carboniferous pelites inducing a metamorphic aureole in this host rock. The major tectonic deformation in the last stages of this orogeny produced a fracture network that conditioned the emplacement of ore veins. These hydrothermal veins consist mainly of galena, sphalerite, chalcopyrite, pyrite, barite, quartz, ankerite and calcite hosted by Palaeozoic basement and the granitoids (Lillo 1992). A dense swarm of subparallel, nearly-vertical mineralized dykes has developed into the granitic Linares area. In the La Carolina sector, the geomechanical behaviour of the Palaeozoic materials controls the feasibility of the exploitations, and is only interesting to be mined when the host rock consists of abundant quartzite levels or is affected by contact metamorphism.

This is a region with a Mediterranean climate, an average precipitation around 550 mm/a and scarce surface water resources. The increasing demand of additional water resources –especially for irrigation- and the lack of important aquifers in the vicinity have led to the pumping of groundwater directly from mine shafts and galleries, which are partially flooded at present.

Samples of waters were collected from the main shafts, drainage adits and rivers in both sectors to i) document the geoenvironmental signature of lead mines in surface and groundwater, some 20—30 years after the mines were last active and ii) provide baseline data and evaluate groundwater chemistry with respect to water quality guidelines for different uses.

Hydrogeological context and mine water uses

The Linares batholith is crossed in a roughly N-S direction through its western part by the Guadiel River and most of the granitic area drains to it. The NE part of the batholith is drained by the Guadalimar River. Both are tributaries of the Guadalquivir River, the Andalusian main stream, which flows from E to W a few kilometers to the south of the studied area.

In the Linares area topography is gentle and the overall landscape is characterized by a mesa-like morphology. During the late 1950s the exploitations needed to pump water from depths of more than 500 m in some mines and, to minimize elevation costs of pumping, a 12 km drainage adit was built at a depth of around 200 m, crossing the most important veins. The aim was to connect a number of main shafts and to allow gravity drainage towards the Guadalimar River, to the SE. The adit was designed to evacuate 600 L/s. It was operational only during a short period, because at the early 1990s the last mining activities ceased, leaving an important volume of the mining works flooded after the stopping of the dewatering operations.

At present, this main adit drains most of the granite body and imposes the potentiometric level in sectors around its pathway. Growing requirements of groundwater resources for irrigation of new plantations of olive trees in the area –which is at present an economically profitable activity- have led to pump directly (unitary yields up to around 50 L/s) from the abandoned shafts, with an average annual extraction of 6 hm^3 (Table 1). Mine water has also been used for industrial supply (1 hm^3/a) and, to a lesser extent, for domestic use. Altogether, an average annual volume of 7 hm^3 of water pumped in mining voids has been estimated. This is affecting the discharge of the adit that now is frequently in the range of 20—50 L/s.

In addition, this area is characterised by a high geochemical background in soils and sediments (Martínez et al 2007) and large areas are covered by tailings and waste dumps, constituting an additional source for metals in surface waters.

On the other hand,, the La Carolina sector is characterized by a relatively steep relief, of alternating hills and valleys, which has conditioned –for dewatering purposes- the development of a lot of drainage adits which are discharging along creeks and rivers that drain into El Rumblar reservoir. This dam was constructed as part of the Andalusian Government's regional flood control and drinking water supply program. Although several mine waste dumps are present on its headwater catchment, discharge from mine adits is volumetrically insignificant during most of the year (Hidalgo et al 2009).

Mine water and surface water quality

Different campaigns of hydrochemical monitoring, both in surface waters and in groundwaters, have been carried out in the two sectors which made up the study area. A summary of the most significant hydrochemical variables for mine and surface waters is presented in Table 2.

In this table, the two main sectors of concern are indicated separately and mine waters and surface waters are distinguished. Fig. 1 shows some scatter plots of the most significant physical-chemical variables of Table 2.

Low pH values, of less than 4, have only been identified in the La Carolina sector. In contrast, the Linares sector – both shafts and drainage adit – shows some net alkaline values. Concerning average individual concentrations, the La Carolina sector exhibits higher contents of sulphate, magnesium, iron and manganese than the Linares sector. Also La Carolina mine waters are the most mineralized of the four groups in Table 2. This is particularly noticeable in some samples which reach up to 5000 µS/cm, which it is about 4 times the average value.

Table 1 *Annual pumping extractions from flooded mines in the Linares district.*

Uses	Volume (hm^3/year)	%
Agriculture	6.00	85
Domestic supply	0.05	1
Industry	1.00	14
Total:	**7.05**	**100**

Table 2 *Average physical-chemical characteristics of mine and surface waters (concentrations expressed in mg/L) for the Linares-La Carolina mining district: CM, La Carolina mine waters; CS, La Carolina surface waters; LM, Linares mine waters; LS, Linares surface waters; N, number of samples; E.C., electrical conductivity*

Group	N	E.C.(µS/cm)	pH	Pb	Fe	Mn	Ca^{2+}	Mg^{2+}	Na^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}
CM	45	1418	6,3	0,07	18,5	5,1	149	88	27	22	723	242
CS	18	571	7,1	0,003	2,7	0,34	50	34	18	15	223	136
LM	20	1050	7,5	0,04	0,3	1	122	32	48	51	297	258
LS	26	845	7,4	0,04	0,4	0,6	84	28	47	55	120	304

A net direct relationship between sulphate content and E.C. is inferred from fig. 1b. This has been interpreted as the result of sulphide oxidation in the old mine voids (pyrite is widespread through the ore complex). No acidity generation has been clearly identified in association with this process in the Linares sector, whereas acidic waters appear in the La Carolina sector. This generates a great amount of sulphates (700 mg/L), calcium (150 mg/L) and magnesium (90 mg/L) in the water and also led to the existence of high contents in Fe (average value of 18 mg/L) and Mn (5 mg/L).

The two remaining scatter plots of fig. 1 illustrate the two main analyzed metals with the pH. In both cases, a general inverse relation between the variables is suggested. In these figures, acidic waters appear as outliers.

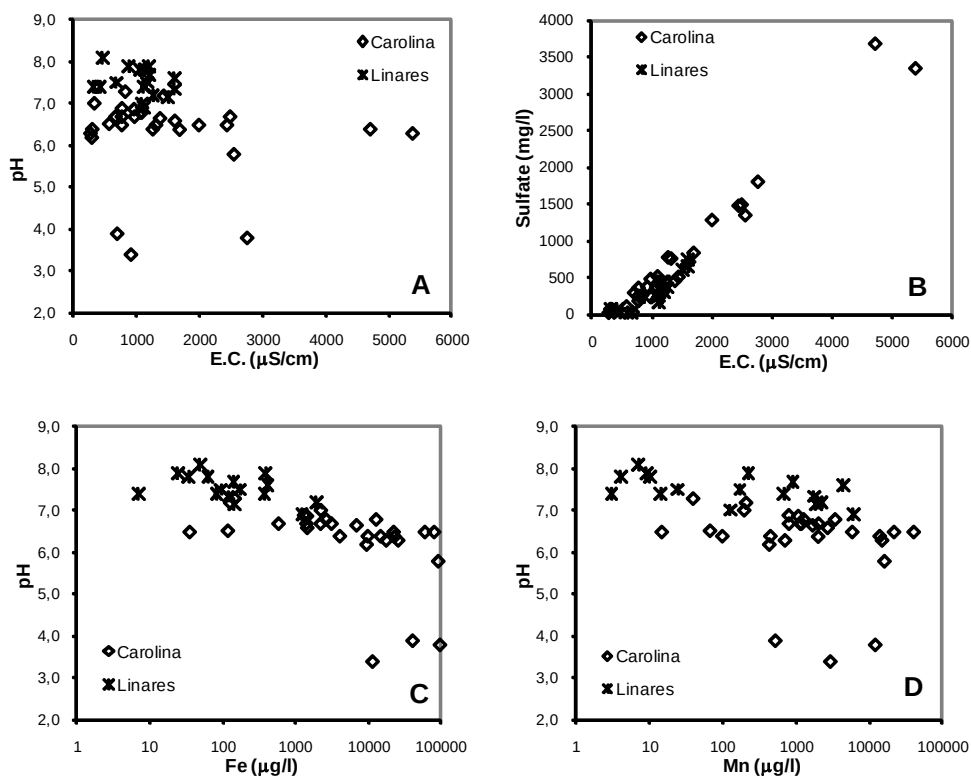

Figure 1 *Hydrochemical plots of mine water samples: electrical conductivity vs pH (A) and sulphates (B); pH vs iron (C) and manganese contents (D) (note logarithmic horizontal scale in C and D)*

Conclusions

There is a scarce mobilisation of heavy metals into the waters in the Linares area, which are characterized by net alkaline conditions. However, the hydrochemical type of these waters is characterized by average sulphate content (300 mg/L) that slightly surpasses the maximum limit established by the European guideline for drinking water. Although the mine water quality is, in general, optimal for most of the uses, some exceptions are registered in the northwest area of Linares. In this zone, mines are not connected to the main drainage adit and important oscillations of the piezometric level occur due to intensive pumping. These mine waters present a high Mn content (several mg/L) and reverse osmosis has been used to eliminate it in order to use water for industrial and urban supply.

On the other hand, acid mine drainage is detected in the La Carolina sector, where pH values range from 3.4 to 7.3 and mine waters are characterised by a wide range of mineralization (from 300 µS/cm to 5500 µS/cm, approximately). As far as metal concentrations are concerned, iron and manganese reach tens of mg/L, not only in acid mine drainage adits but also in some alkaline waters. Although some mine waters of the La Carolina district are acid, the mining effluents are diluted in a fast and efficient way by waters of surface run-off, which diminishes considerably the environmental impact on the quality of the water resources.

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