Scientific, Educational, and Environmental Considerations Regarding Mine Sites and Geoheritage: A Perspective from SE Spain

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Abstract Should abandoned mine sites be eligible for some official protection under the umbrella of geoconservation? Providing they have enough educational and scientific value, the answer is affirmative, and we suggest that they should be granted protection at the level of geoheritage sites. Some may see mining as an environmental disaster, but others, with a more geologically oriented mind, may perceive mining as a blessing. Mining unveils the geology, thus allowing a more comprehensive vision of geological features such as rock units, faults, minerals, etc. We analyze the advantages and disadvantages of abandoned mines and districts as geologic observational sites, through the analysis of two mining districts from SE Spain: Mazarrón and Cartagena–La Unión. We propose that if an abandoned mine site or district has enough geological value, not only the mining site but also the whole geologic block hosting the ore deposits should also be protected. In this respect, the Sierra de Cartagena, hosting the Cartagena–La Unión district, is a valuable geological asset where an important chapter of the Alpine and late Alpine geologic history of SE Spain is written.

Keywords SE Spain · Mine sites · Geoheritage · Mazarrón · Cartagena–La Unión

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Introduction

Abandoned mine sites and mining districts, providing they are important enough, may be granted the status of "site of cultural or historical heritage." However, it would be difficult to find many that are under consideration as geoheritage sites. Given the huge educational value of many old mines and districts, one may wonder why these sites are not adequate for geoheritage consideration. People mined the planet for thousands of years, first to obtain stones for crucial activities such as hunting (e.g., obsidian for arrowheads), or looked for minerals to paint in caves and rock walls (e.g., from hematite: red ochre, or limonite: yellow ochre), eventually extracting metals from minerals (e.g., copper from malachite). There is no way to describe in a few words how important mining has been and continues to be for us. However, if mining is so important for society, why then are mine sites usually excluded from the geologic heritage? Perhaps, the roots of this misconception can be traced to the classic compilation work of Sharples (2002), who proposed that:

> Geoheritage comprises those elements of natural geodiversity which are of significant value to humans for non-depleting purposes which do not decrease their intrinsic or ecological values. The import of this definition is that it implies a distinction between the utilitarian resource values derived from the removal, processing or manipulation of rocks, landforms and soils by means such as mining, engineering or agriculture, and the conservation values of rocks, landforms and soils as heritage in their natural state.

In making a case for the treatment of old mining sites as valuable contributors to geoheritage, it may help to consider an example. Let us take the case of the lead–silver Naica mine in Mexico, where exploration works revealed the existence of giant, faceted, and transparent single crystals of gypsum as long as 11 m (Fig. 1) (García-Ruiz et al. 2007). This is not just a singular oddity, because a similar finding was recorded at the huge El Teniente mine in Chile, where 6-m-long, 1.5-m-wide, gypsum crystals were found in caves formed within a breccia unit (Braden Formation) (Camus 1975). Mines are not just sites where the natural state of nature has been altered. Apart from economic and therefore social considerations, they play another crucial role: they unveil geological objects that under normal circumstances, no one would see. In this respect, one may look at mine sites either as a problem or as an opportunity. We examine both aspects in this work through the study of two examples from SE Spain: the Mazarrón and Cartagena La Unión districts, both having a certain level of protection as "sites of cultural heritage" but lacking recognition from the perspective of geoconservation.

The Mazarrón and Cartagena–La Unión Districts: Unusual Geological Scenarios

Peculiar Volcanic and Metallogenic Features

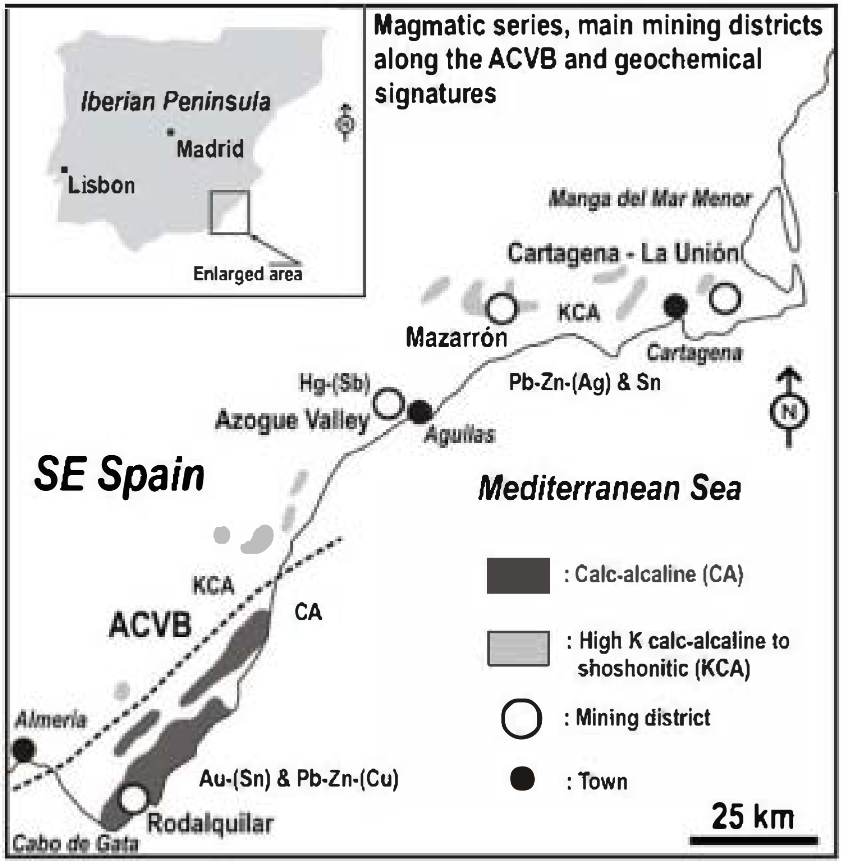
The geology of SE Spain (Almería and Murcia regions) is characterized by the presence of two of the most important Alpine complexes: Alpujarride and Nevado Filábrides. These units were intensively folded and thrust during the late Oligocene early Miocene, and they later underwent extensional collapse through major detachment systems in the middle-late Miocene (e.g., Doblas and Oyarzun 1989; Platt and Vissers 1989). The latter episode was accompanied by important calc-alkaline to high calc-alkaline and shoshonitic volcanism (andesites, dacites, rhyolites) along the Almería Cartagena volcanic belt (ACVB) (Fig. 2), whereas sedimentation took place within restricted marine sedimentary basins. The volcanism triggered hydrothermal activity that led to the formation of important ore deposits of Au at Rodalquilar (Almería) and Pb (Ag) Zn and Sn at Cartagena La Unión (Oyarzun et al. 1995). This is a most peculiar arrangement of volcanic series and ore deposit types, the whole occurring within a short and narrow belt of ~160×20 km between the localities of Almería and La Manga del Mar Menor (Fig. 2). We may find an equivalent metallogenic and volcanic scenario in the Chilean Bolivian Andes, but in that case, we are dealing with phenomena developed at an immensely larger scale (Oyarzun et al. 1995). Furthermore, while the Andean volcanism is related to the subduction of the Nazca plate, in SE Spain, there is no subduction, but the extensional collapse of the Alpine orogeny triggered the volcanic activity (Doblas and Oyarzun 1989; Oyarzun et al. 1995; Benito et al. 1999). Thus, the ACVB and associated ore deposits can be regarded as a model-like, dwarfed representation of the volcanism and metallogenesis from the Central Andes but that nonetheless formed through an entirely different plate tectonics scenario (Oyarzun et al. 1995).

Fig. 1 Treasures unveiled by underground mining. View of giant gypsum crystals (selenite variety) at the Naica Pb–Ag mine. The crystals display wonderfully preserved prismatic crystal faces (García-Ruiz et al. 2007). See miner for scale. **Photograph**: Javier Trueba—Madrid Scientific Films

The Mazarrón District

The Mazarrón Pb (Ag) Zn mining district, inactive (Figs. 3 and 4a) (Rodríguez and Hidalgo 1997; Arana 2007; Oyarzun et al. 2010), is located close to the town of Mazarrón, 4 km from the Mediterranean coast in SE Spain. The site was mined, although intermittently, since Roman times (200 BC to 300 AD) (Manteca Martinez et al. 2005). The Romans mined lead, and later working was for alum (aluminum sulfate: alunite) during the fifteenth to sixteenth centuries, then for the iron oxide-rich alum wastes (the so-called almagres; 1774 1953), and finally for lead, silver, and zinc during the nineteenth to twentieth centuries (until the early 1960s) (Rodríguez and Hidalgo 1997; Manteca Martínez et al. 2005; Martínez Alcalde 2005). Volcanic activity gave rise to high-K calc-alkaline andesites, dacites, and rhyodacites of Tortonian to Messinian age that were emplaced as subvolcanic domes within a basement constituted by the Nevado Filábrides and Alpujárrides complexes (Fig. 3). Pyroclastic rocks such as ashfall deposits are also present in the area. The volcanic rocks form an inner ring within the horseshoe structure bounding the Mazarrón basin. The Mazarrón basin was infilled during Tortonian Messinian and Pliocene time by marine sediments comprising marls, sandstones, conglomerates, and coquina limestones (Fig. 3). The district hosts Pb (Ag) Zn epithermal deposits of the vein stockwork type that were mined at

Fig. 2 The Almería–Cartagena volcanic belt (*ACVB*) and main mine districts. Volcanic series after López Ruiz and Rodríguez Badiola (1980). Districts after Oyarzun et al. (1995) and Viladevall et al. (1999)



Coto Fortuna, Pedreras Viejas, and San Cristóbal Perules (Figs. 3 and 4a). These sites are characterized by the presence of dacitic to rhyodacitic domes that underwent strong and pervasive advanced argillic hydrothermal alteration, with formation of kaolinite, alunite, and silica. The main ore minerals are pyrite, sphalerite, and Ag-bearing galena (up to 15 20% Ag), whereas other sulfides include chalcopyrite, tetrahedrite-tennantite, arsenopyrite, cinnabar, stibnite, and berthierite. Secondary minerals include cerusite, anglesite, smithsonite, azurite, and malaquite, whereas gangue minerals include quartz, calcite, siderite, dolomite, and gypsum (Arana 2007).

Fig. 3 Geology of the Mazarrón mining district indicating location of main mine sites. *NFA* Nevado Filábrides and Alpujarrides Complexes. Simplified after Oyarzun et al. (2010)

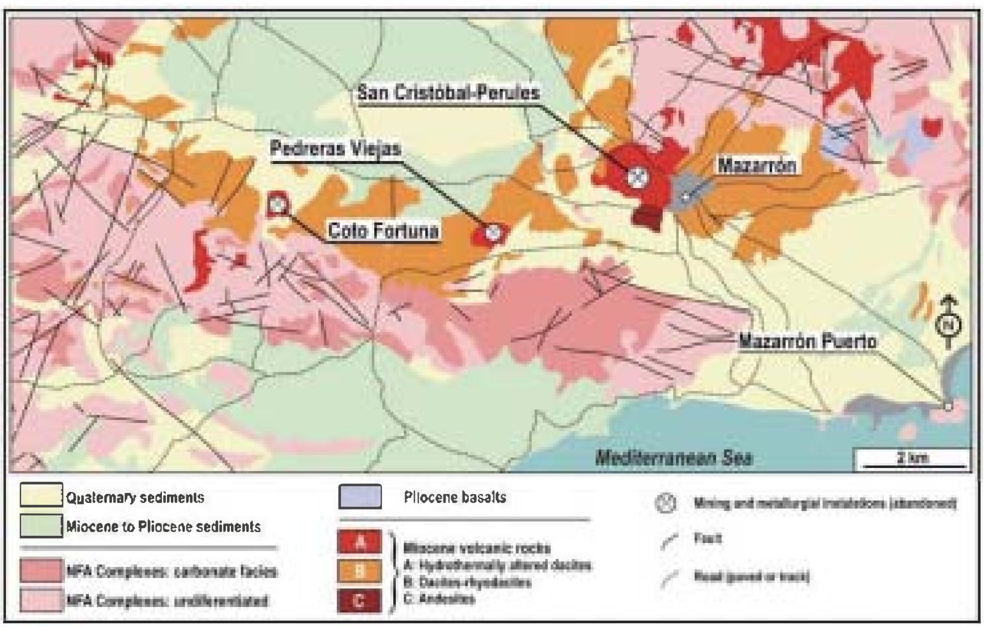


Fig. 4 Images from the Mazarrón and Cartagena–La Unión districts. **a** Main entrance to the San Cristóbal–Perules mine site; note the *bright colors* of tailing deposits. **b** The Emila open pit, site of one of the best examples of manto-type mineralization, which is being progressively buried by the debris from the construction industry. **c** The La Crisoleja dome and tin deposit, a singularity in Europe

The Cartagena La Unión District

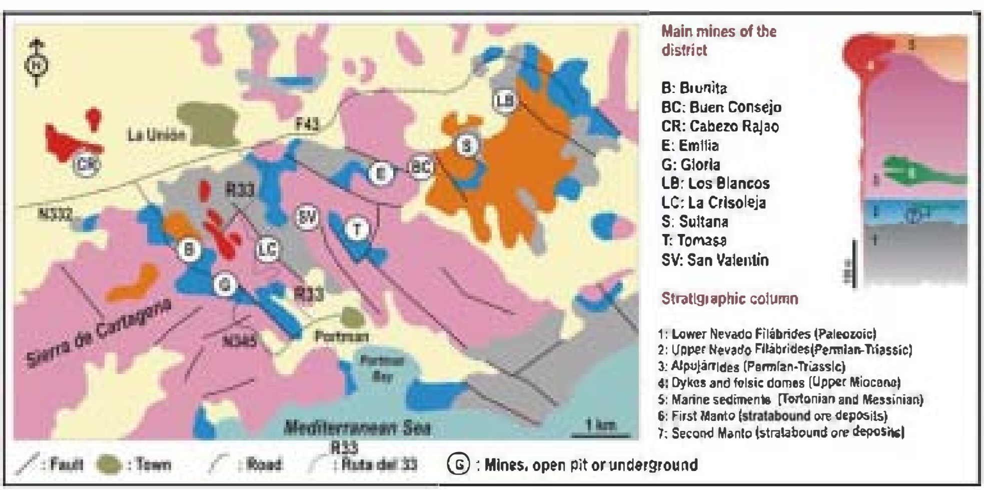
The mining district of Cartagena La Unión, inactive (Figs. 4b, c and 5) (Oen et al. 1975; López García et al. 1988; Manteca Martínez and Ovejero Zapino 1992; López García et al. 2010), is one of the most important geological and mining sites of Spain, and together with the districts of Rodalquilar (Oyarzun et al. 2009) and Mazarrón (Oyarzun et al. 2010), is an extraordinary example of the many relationships between Miocene magmatism, tectonic, and metallogenic processes in SE Spain (Oyarzun et al. 1995). The Cartagena La Unión district covers an area of about 10×5 km and contains the highest density of Pb Zn ore deposits of the Betic Ranges and one of the largest in Spain (Fig. 5). Centuries of mining, especially in the late nineteenth and twentieth centuries at the Sierra de Cartagena, resulted in a landscape where the visitor will find all kinds of traces of past mining activities.

Modern mining at the Sierra de Cartagena can be divided into two periods. The first comprised traditional, underground operations that were active until the 1950s. From the 1960s onward, the Sociedad Minero Metalúrgica Peñarroya España (a French mining group) began large open pit mining operations, which led to the generation of large volumes of tailings and mineral dumps, and eventually to huge abandoned pits.

The sierra is mainly formed by the basement complexes of Nevado Filabride (Precambrian/Paleozoic to Triassic) and Alpujarride (Permian to Triassic) (Fig. 5), which crop out as a series of overlapping thrust sheets of Alpine age. During the late Miocene, the basement units underwent gravitational (extensional) collapse, a phenomenon that was accompanied by (1) a major high-K calc-alkaline volcanism comprising intermediate to felsic (andesite, dacite, rhyodacites) volcanic rocks, dykes, and domes; and (2) Miocene to Pliocene marine sedimentation on extensional basins (Fig. 5).

The ore deposits are of different types (Fig. 6a d), and from a morphological and mineralogical point of view, can be divided into different groups (Oen et al. 1975): (1) Mantos these are stratabound ore deposits hosted by the Nevado Filabride (second manto) and Alpujarride (first manto) complexes (Figs. 4b and 6a). Both manto units have

Fig. 5 Geology of the Cartagena–La Unión mining district (including stratigraphic column) indicating location of main mine sites. Simplified after Manteca Martínez and Ovejero Zapino (1992)



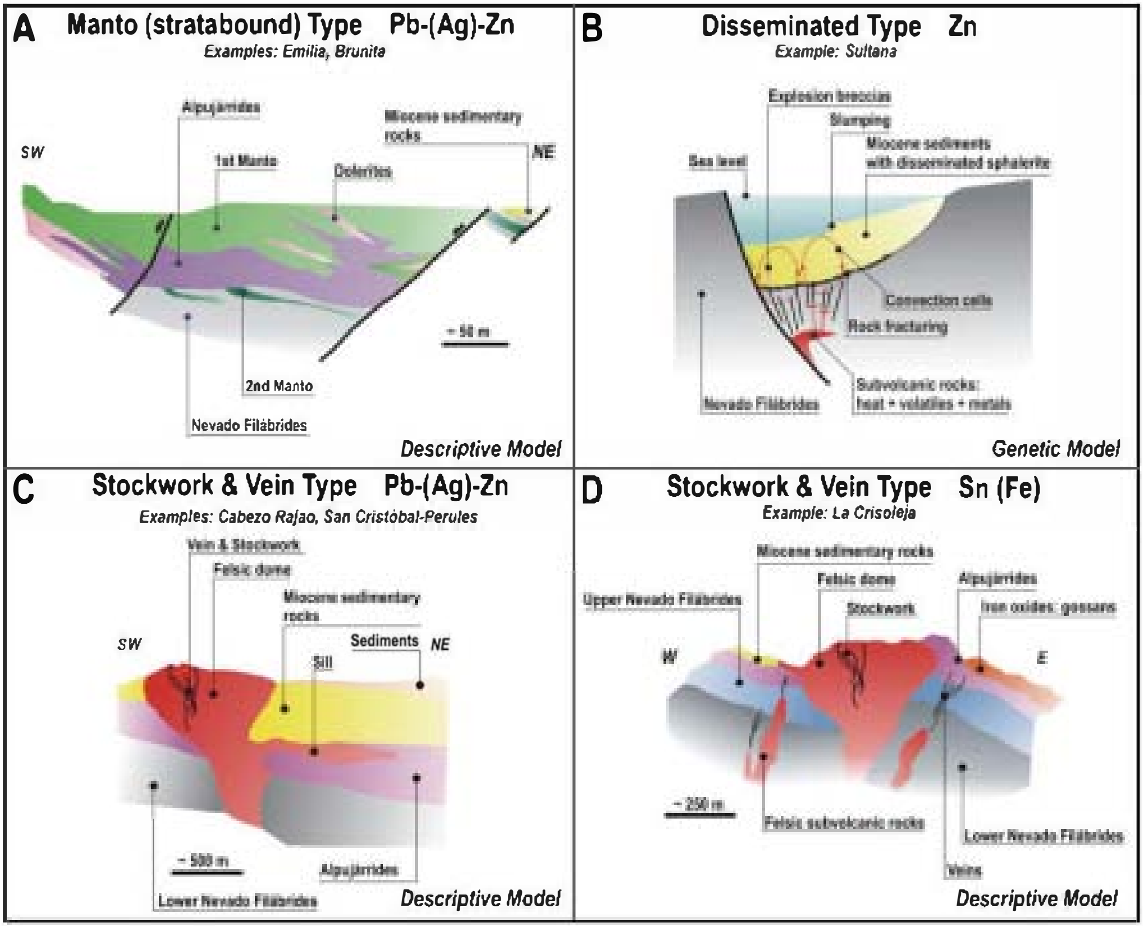


Fig. 6 Main ore deposit types from the Cartagena–La Unión district including San Cristóbal–Perules (Mazarrón). Based on Manteca Martínez and Ovejero Zapino (1992)

two distinct mineral assemblages: (a) greenalite magnetite sulfide carbonate silica and (b) chlorite sulfide carbonate silica. Most of the lead and zinc produced in the district were extracted from these manto-type deposits. (2) Disseminations in the Miocene marine facies the best example is found at the Sultana mine, where the ore forms irregular bodies in the Miocene conglomerates and marls (Fig. 6b). This is a sphalerite-rich mineralization with pyrite, marcasite, and galena as minor phases. (3) Veins these are tabular deposits that developed in highly fractured domains in the complexes and had little economic importance. (4) Stockworks in felsic domes such as those of Cabezo Rajao (Fig. 6c) and La Crisoleja (Figs. 4c and 6d). The ore bodies consist of complex stockwork zones with associated splay-mineralized veins. Although the Cabezo Rajao mineralization is typically of the Pb Zn type (Fig. 6c), at La Crisoleja, there is a unique mineral assemblage rich in tin and oxides (Figs. 4c and 6d). (5) Oxidation zones the near surface ore bodies underwent strong oxidation processes that resulted in the formation of the so-called monteras (gossans) with a complex mineralogy of oxides, sulfates, and native elements such as silver and copper (López García et al. 1988).

On the Educational and Social Values of Mazarrón and Cartagena–La Unión

Sharples (2002) suggested that geoheritage sites should be of value to humans, providing scientific evidence of the past development of the Earth, constituting sites of importance for research and education, including features of recreational or tourism significance, and having features that form the basis of landscapes that have contributed to the sense of place of particular human communities. We believe that geological settings such as those of Mazarrón and Cartagena La Unión fulfill these conditions. Both districts are contained within a region with a unique geological history involving (1) the buildup and final collapse of an Alpine orogeny (Betic Ranges); (2) volcanism that led to generation of calc-alkaline to high-K calc-alkaline and even shoshonitic volcanic series; and (3) the development of different styles of hydrothermal activity that ultimately led to formation a myriad of ore deposits types (Fig. 6) and unusual mineral parageneses. In this respect, the following facts must be highlighted. The association of greenalite magnetite with Pb Zn ores in the manto-type ore deposits from Cartagena–La Unión (Fig. 6a) constitutes a most unusual case unknown anywhere else (Oen et al. 1975). Besides, metallogenic clusters (groups of genetically related ore deposits) are usually very simple, containing a single or two (at the most) ore deposit types. Cartagena–La Unión contains more than four fundamental types including stratabound, disseminated vein, and stockwork (Fig. 6). Furthermore, this account neither includes minor types nor the variety of metallic signatures (Pb, Zn, Ag, and Sn).

For these reasons, the Mazarrón and Cartagena–La Unión districts are privileged sites for research and education, and have provided the perfect geologic–metallogenic scenario for numerous research papers and doctoral theses. Besides, every year, these districts attract visiting lecturers and students of geological sciences from Spain and other European countries. In terms of recreational or tourism significance, we must highlight the activity of the Tourist Consortium of the Sierra Minera (formed by the Autonomous Community of Murcia and the towns of Cartagena and La Unión), which carries out important actions to improve environmental conditions while preserving the important mining heritage. The Consortium has developed heritage preservation projects such as those of Cueva Victoria, Ruta del 33, and the La Unión Mining Museum. The *Ruta del 33* (The 33 Trail) is a particularly relevant educational project that consisted in rehabilitation of an old mine trail crossing the Sierra de Cartagena from La Unión to Portman Bay (Fig. 5) (Manteca Martínez et al. 2008). The visitor can have access to old mine workings (e.g., the Agrupa Vicenta underground mine) and the local geology.

Finally, regarding Sharples's "landscapes that have contributed to the sense of place of particular human communities," no other people in the world feel more for their places than miners, and this tradition remains strong at La Unión, where it gave rise 50 years ago to a major annual musical festival, the so-called *Cante de las Minas*, representing the flamenco history of the mining tradition (Fundación Cante de las Minas 2010).

Environmental Pros and Cons

The Facts: Valuable but Polluted Sites

Despite the unquestionable educational and social values of Mazarrón and Cartagena–La Unión, there are aspects that should be further analyzed. Mining, like most work-related activities, creates disturbances in the natural environment, from the imperceptible to those that represent clear hazards. The environmental impact of an activity may be defined as the difference in environment from the time when the activity begins, when the activity takes place, to the time when it is completed. These issues were not formerly considered as risk factors, but are now viewed with great concern. Thus, at present, there are strict rules about the impact of mining operations, which include regulation of the liquid wastes, emissions of dust, gases, and noises and the restoration of the landscape, etc. With respect to the mining districts of Mazarrón and Cartagena–La Unión, there are a number of environmental problems, and the most relevant are the following (Robles-Arenas et al. 2006; Oyarzun et al. 2010): (1) Major areas covered by old mineral dumps. These areas have significant visual impact and a potential for the leaching of heavy metals. (2) Tailing deposits derived from the flotation of sulfides. These tailings are rich in heavy metals such as lead and zinc (among others), and have the potential for acid leaching of heavy metals. Due to the small particle size and wind patterns in the area, the tailings can also induce airborne contamination. (3) Abandoned open pit mines. Some of these have been used for storage of waste, sometimes with disastrous results. (4) The formation of acid mine drainage (AMD) in some of the abandoned sites, such as Brunita (Cartagena–La Unión) and San Cristóbal–Perules (Mazarrón). (5) Abandoned buildings, some in dilapidated condition. (6) Agricultural activities in some areas adjacent to abandoned mining operations such as in the vicinity of Cabezo Rajao (Cartagena–La Unión) and San Cristóbal–Perules (Mazarrón).

However, even environmental hazards can have a positive side from a scientific and educational point of view. AMD formation at San Cristóbal–Perules provides unique conditions for the observation of mineral formation, such as complex sulfates and hydroxides. Besides, given the Mediterranean climate of the region, instead of a permanent flow of AMD, what usually forms are spectacular seasonal pools of deep red to orange-colored waters (Fig. 7a–d) (Oyarzun et al. 2010). Rainfall events cause both increases and decreases in acid and metal concentrations, and the process does not end until pyrite is fully weathered, which can take hundreds to thousands of years (Nordstrom 2009). Long dry spells result in gradual increases in heavy metal concentration, whereas sudden large increases are observed as the rains begin. However, as rainfall reaches its peak, the solutions become diluted (Nordstrom 2009).

Cleaning and Preserving Contaminated Mine Sites of Great Value: A Conflictive Issue?

If abandoned mines from Mazarrón or Cartagena–La Unión are to be regarded as potential geoheritage sites, then a sound and wise policy on land reclamation should be put into action. Any work should start with remediation

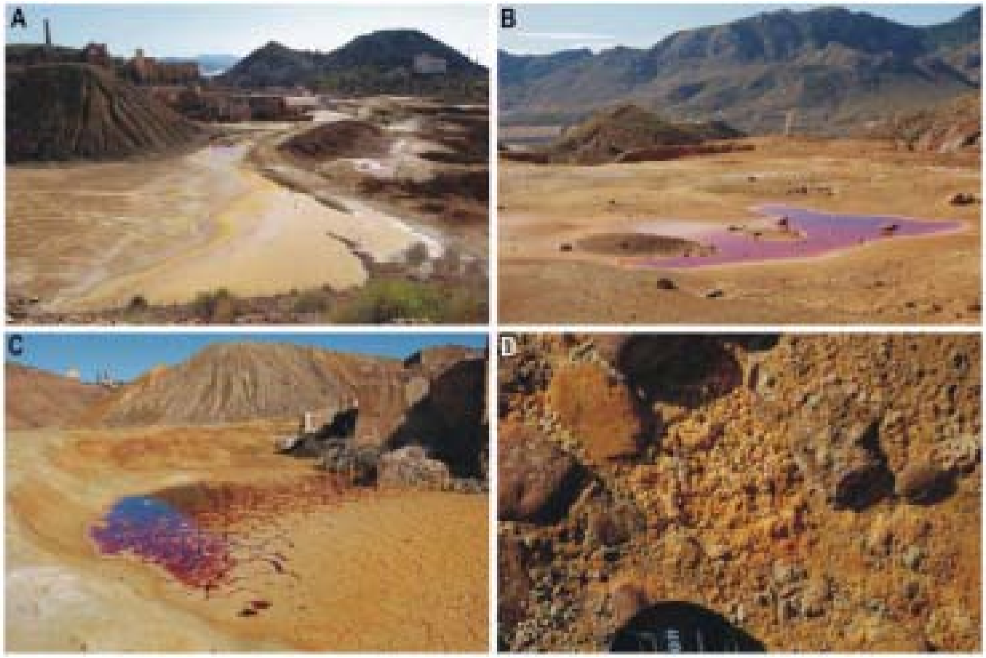


Fig. 7 AMD at San Cristóbal-Perules (SCP, Mazarrón district). **a** The industrial setting in which AMD forms. Pyrite in the tailings is oxidized $4FeS_2+14O_2+4H_2O \rightarrow 4Fe^{2+}+8SO_4^{2-}+8H^+$ thus forming sulfuric acid and ferrous iron; in turn, the latter will oxidize to ferric iron $4Fe^{2+}+O_2+4H^+ \rightarrow 4Fe^{3+}+2H_2O$, eventually leading to formation of goethite $Fe^{3+}+2H_2O \rightarrow 4FeO(OH)+3H^+$; oxidation of pyrite is catalyzed by chemolithotrophic bacteria such as *Acidithiobacillus ferrooxidans* (=*Thiobacillus ferrooxidans*) (Russell and Hall 1997; Valdés et al. 2008). **b** A seasonal pool of AMD. **c** Drying AMD pool leaving behind desiccation cracks. **d** The SCP "natural laboratory" displaying formation of complex metal (Pb, Zn, Fe) bearing sulfates and goethite precursor mineral phases

measures, oriented to the elimination, correction, mitigation, or removal of contaminants from the sites that could have adverse effects on the environment or human health. In this respect, garden-like restoration of a polluted site will not solve the many environmental hazards associated with heavy metals and metalloids. We may hide the contaminated land with clean topsoil, and we may even plant some flowers and trees, but the problem will not fade away (Martinez Coronado et al. 2010). Metals and metalloids will keep contaminating aquifers, and if erosion is not kept at bay, the metals will eventually find their way to the watercourses. Given that the region is subject to strong flash floods, the latter is likely to happen (Oyarzun et al. 2010).

On the other hand, one may wonder whether a mine site that has undergone sound remediation and restoration will ever be regarded again as "proper" mine site. In fact, if tailings and rock wastes are totally removed, and the area covered with clean soil and plants, the site may lose a great deal of its educational value. For example, if the tailings are completely removed, AMD will not form; therefore, there will be no way to observe anymore a complex, natural chemical phenomenon such as the oxidation of sulfide ores. Let us be clear in this respect: AMD forms with or without human intervention, and the best possible example is the Tinto River in Spain (González-Toril et al. 2003). There, the extreme conditions of the habitat are the consequence of active chemolithotrophic microorganisms thriving in the mineral substrates of the Iberian Pyrite Belt (Amils et al. 2007). Thus, AMD ponds or streams are not to be regarded just as another form of active pollution, but as complex microecosystems that may even offer biological clues about early life on Earth (e.g., Russell and Hall 1997; Amils et al. 2007).

Compromising

It is hard to find a place in Europe in pristine, original condition. Millennia of human occupation have profoundly modified not only the original ecosystems but also the landscape as well. Man modified the woodlands to sustain agricultural activities and to obtain wood, modified the rivers to use them as highways of commerce, and penetrated the mountains to facilitate communication, while creating the most complex network of roads and railroads throughout the continent. Even the praised Spanish *dehesa*, an agro-silvo-pastoral system commonly formed by open evergreen oak woodland (e.g., *Quercus rotundifolia*), is man-made. Clearly, man modifies nature, first for survival and then to obtain benefits. Having said all this for Europe, can we really trace a clear boundary between pristine and man-modified nature in this continent? We suggest that in the same way we can enjoy navigation along the wonderful landscapes surrounding the *Canal du Midi* in southern France (a man-made waterway opened in 1681), we can also marvel at the rock exposures left behind at some mining sites.

Clearly, we are not suggesting here that mine wastes should be regarded as wonders but that the unveiled rocks and mineralized structures at some sites of great geological value should receive recognition and be awarded geoheritage site status. We support the views of the group Friends of Canadian Geoheritage (Donaldson 2005), whose interests extend to stone in heritage buildings, distinctive features in road cuts, quarries, and abandoned mines, as well as the cultural history of such sites. This group and the Canadian Geoheritage Committee propose that geoheritage sites should (1) expose a unique or critical record of natural history; (2) contribute to understanding the natural history of the region; (3) be scientifically important, or of significant educational utility; and (3) offer distinct esthetic and cultural values. Based upon this definition, both Mazarrón and Cartagena–La Unión qualify for designation.

Besides, given that ore deposits are not random singularities, but are intimately related to their host formations and regional and local structures, we suggest that not only the ore deposits but also the regional geological features should receive some level of protection. Equivalent proposals have been put forward in Spain for the Almadén District and the Iberian Pyrite Belt (García-Cortés et al. 2001; García-Cortés 2007). An example is the Sierra de Cartagena (Fig. 5) which is a mountainous block that extends east–west along 25 km of coastline between the city of Cartagena and Cabo de Palos. The highest point is the summit of the Sancti Spiritus (431 m) hill, in the vicinity of Portman Bay. The landscape of the Sierra de Cartagena is marked and transformed by centuries of intense human activity, and hosts valuable archeological treasures from its industrial and mining past. For this reason, the area was declared of cultural interest in the category of Historic Site. But the interest of Sierra de Cartagena extends also to the Alpine and late Alpine evolution of this European realm.

Economic recession has slowed the building of villas, hotels, and marinas (the main menacing force in this zone) in SE Spain and elsewhere. Providing that the country starts moving to sustained growth once again, the geology of the Sierra de Cartagena will continue to disappear (as before) under tons of concrete and bricks (López García et al. 2007). Let us hope that some status of geological protection can be granted to this realm before it is too late.

Conclusions

We see no compelling reasons for denying a geological protection status, such as geoheritage site, to mines with proved valuable geological features. From the viewpoint of conservation and under an educational perspective, mining can be a blessing for geologists because both open-pit and underground operations unveil geological features. In this respect, the Naica mine in México, with its giant gypsum crystals, provides a nice example of the reason why some mine sites could and should receive the geoheritage site status. Given that our proposals are directed to old, abandoned mine sites, the environmental aspects of this matter should be also taken into consideration. However, even environmental hazards such as AMD pools (like those of Mazarrón and Cartagena–La Unión) could be entitled to some protection. As explained above, their unique micro-ecosystems can be extremely valuable for scientific research.

Finally, we propose that if an abandoned mine site or district has enough geological value (such as Mazarrón or Cartagena–La Unión), not only the mine(s) should be protected but also the geologic block hosting the ore deposits. In this respect, the Sierra de Cartagena is a most valuable scientific asset containing key aspects of the Alpine and late Alpine geologic history of SE Spain.

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