The beach placer iron deposit of Portman Bay, Murcia, SE Spain: the result of 33 years of tailings disposal (1957–1990) to the Mediterranean seaside

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Abstract Between 1957 and 1990, the Peñarroya Mining and Metallurgical Company (SMMPE) disposed about 60 million tonnes of tailings materials directly to the Mediterranean Sea. A substantial part of it (12.5 Mt) was dragged back by the sea currents progressively infilling the Portman Bay (Murcia, SE Spain), thus making the shoreline advance between 500 and 600 m seaward. The Roberto froth flotation plant processed mineral from manto-type deposits belonging to the Sierra de Cartagena-La Unión lead-zinc district. One of the mineral assemblages present in these deposits comprises greenalite, magnetite, sulfides, carbonates, and silica. Despite that magnetite recovery was undertaken by SMMPE between 1959 and 1967, we estimate that magnetite contained in the tailings hosts a substantial resource that could be as large as 2.3 Mt of iron ore. The ore contains magnetite $\pm$ hematite $\pm$ siderite. Tidal waves and sea currents led to gravimetric classification of the tailings material, with concentration of the dense iron oxides in the sandy fractions, eventually forming a coastal placer iron deposit. A major problem for magnetic separation is the intimate intergrowth between magnetite, hematite, and siderite. Besides, the sands contain large concentrations of Pb (0.27 %), Zn (0.72 %), and As (559 ppm).

Keywords Iron ore · Beach placer deposit · Magnetite · Portman Bay · La Unión · Spain

Introduction

In 1957, the Peñarroya Mining and Metallurgical Company (SMMPE) opened the Roberto bayside Portman ore concentration facility to treat complex ores from mining deposits belonging to the Sierra de Cartagena-La Unión mining district (Sierra de Cartagena) (Oen et al. 1975; Manteca and Ovejero 1992) (Fig. 1a, b). With an initial capacity of 1,500 tonnes/day, the plant reached peak production at 10,000 tonnes/day in the late 1980s. SMMPE started open-pit mining operations already in 1953 which led to the generation of large volumes of rock waste and tailings deposits in the area of the Sierra de Cartagena, a mountainous structural block that extends east-west along 25 km of the coastline (Fig. 1a). Centuries of mining, especially in the late nineteenth and twentieth centuries at the Sierra de Cartagena had resulted in a landscape with all kinds of traces of past mining activities including extensive waste dumps and tailings deposits, covering most of the space along the narrow and steep valleys. Thus, SMMPE was left with almost no option but to build a mineral concentration facility by froth flotation (the so-called Lavadero Roberto) adjacent to the town of Portman, a seaside location surrounded by mountains (Fig. 1b). Given that essentially no environmental restrictions existed at that time (nor anywhere in the world), it was decided that the tailings are directly disposed onto the sea. About 60 Mt of tailings from the Lavadero Roberto were pumped directly into the sea, beside the bay, leaving behind hazardous (metal-rich) artificial soils and sands and moving the shoreline 500–600 m to the sea (Fig. 1b). From an environmental point of view, this operation meant a huge disaster (Oyarzun et al. 2013), but from the economic geology perspective, something unusual happened: a placer iron deposit

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Fig. 1 **a** Geology and ore deposits from the Sierra de Cartagena coastal block. Numbers in the stratigraphic column denote the following: 1, Lower Nevado Filábrides Complex (Paleozoic); 2, Upper Nevado Filábrides Complex (Permian-Triassic); 3, Alpujarrides Complex

(magnetite-hematite-siderite) formed in the bay. Recent news in the Press media indicates that there is a decision to mine the Portman beach iron-rich sands through a joint venture formed by Acciona (a Spanish Company) and Aria (a German company) (ABC 2013; Portal de la Unión 2013); the latter is currently drilling offshore (a few tens of meters) to assess the resource beyond the beach front. A description of the potential mining site and the geological pros and cons of such an operation follow.

Ore deposits, mineral assemblages, and metallurgical procedures

The mining district of La Unión (presently inactive) (Oen et al. 1975; Manteca and Ovejero 1992) was one of the most

(Permian-Triassic); 4, felsic domes and sills (Miocene); 5, marine sediments (Miocene); 6, first manto; 7, second manto. **b** The bay of Portman at present showing main relevant features. See inset for location in the Iberian Peninsula

important mining sites of Spain and a perfect example of the many relationships between the Miocene magmatism, tectonic, and metallogenic processes in SE Spain (e.g. Oyarzun et al. 1995). The La Unión district covers an area of about 10×5 km that has the highest density of Pb-Zn ore deposits of the Betic Ranges and one of the largest in Spain. The Sierra de Cartagena coastal block is formed by the basement complexes of Nevado Filábride (Paleozoic to Triassic) and Alpujarride (Permian to Triassic) (Fig. 1a), 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 high-K calc-alkaline volcanism comprising intermediate to felsic (andesite, dacite, rhyodacite) volcanic rocks, dykes, and domes, and Miocene to Pliocene marine sedimentation in extensional basins (Fig. 1a). The La Unión ore deposits are

of different types and can be divided into the following groups (Oen et al. 1975): mantos and veins in the Alpine complexes, sulfide disseminations in the Miocene sediments, and stockworks in dome complexes. However, from the Portman Bay perspective, the mantos are the most relevant (Fig. 1a), because most of the ore that fed the Roberto froth flotation plant came from these deposits. However, from 1984 onwards, magnetite-free, sphalerite-rich sulfide ore from the Sultana pit progressively substituted the ore from the mantos.

The mantos are stratabound ore deposits hosted by the Nevado Filábride (second manto) and Alpujárride (first manto) complexes. Both manto units have two distinct mineral parageneses (MP) (Oen et al. 1975; Manteca and Ovejero 1992):

MP-1. Chlorite-sulfides-carbonates-silica.

MP-2. Greenalite-magnetite-sulfides-carbonates-silica.

The latter is particularly relevant to the formation of the placer deposits as it is the only one containing magnetite, whereas siderite is present in both MPs. After milling, the finely grained mineralized material (the “head”) entered the Roberto concentration plant. There the process continued by the so-called froth flotation procedure (e.g., Kawatra 2011), which physically separates particles based on differences in the ability of air bubbles to selectively adhere to specific mineral surfaces (ore minerals) in a mineral/water slurry; the particles with attached air bubbles are then carried to the surface and removed, whereas the particles that remain completely wetted (gangue minerals) stay in the liquid phase, are removed, and form the “tailings.” The usual procedure continued by shipping the “concentrate” (rich in Pb and Zn) to a smelter, whereas the tailings were disposed onto the sea. Given that two minerals had economic interest (galena, PbS; sphalerite, ZnS), the process involved differential flotation, in which first galena and then sphalerite concentrates were generated. According to the systematic analyses of the residues (SMMPE 1970, 1985), the tailings were mainly composed of silica, phyllosilicates, carbonates, and iron oxides and carbonates. A study by MINEMET (1974) established the following mineralogical composition for the tailings (mineral treated during 1973): carbonates (mainly siderite), 35.9 %; phyllosilicates (greenalite, chlorite, clays), 25.7 %; silica (quartz, opal, chalcedony), 20.0 %; Fe oxides (magnetite, hematite, goethite), 15.6 %; and sulfides (mainly pyrite), 2.7 %. In turn, these tailings have a considerable content of heavy metals such as lead and zinc (in the order of 0.20 % Pb and 0.60 % Zn) (Oyarzun et al. 2013).

SMMPE also had a final flotation step to remove pyrite from the initial tailings for the production of sulfuric acid, which was constantly performed through the years except during the period 1965 to 1973. Additionally, the recovery of magnetite was attempted by SMMPE between 1959 and

1967. The process involved magnetic separation of the tailings, but the lack of profitability called for an end of the operation. Thus, after 1967, all the magnetite went with the tailings to the sea shore. The Roberto plant treated (before decommission) 59,655,000 t of sulfide ores from the mantos, and the total amount of sulfide concentrates was 3,418,000 t (SMMPE 1984). The amount of disposed tailings materials is then 56,237,000 t.

We estimate that about 73 % of the tailings (about 41×10^6 t) correspond to MP-2 ore and therefore contains magnetite. On the other hand, 157.7×10^3 t of magnetite concentrate (57.4 % Fe) were obtained from $5,204.3 \times 10^3$ t of tailings between 1960 and 1966 (Table 1), that is, a ratio of about 1/33 (3 % magnetite concentrate in ore). Thus, we may estimate a total of magnetite (in concentrate) discharged to the sea via the following relationship:

$$\text{TMC} = \frac{41 \times 10^6 \text{ t}}{33} = 1.24 \times 10^6 \text{ t}$$

where TMC are metric tonnes of “magnetite concentrate” discharged to the sea if no magnetic separation would have taken place. If we subtract from this figure the actual amount of magnetite concentrate separated from the tailings (Table 1), then we have

$$\text{TMC}_{\text{actual}} = 1.24 \times 10^6 \text{ t} - 0.17 \times 10^6 \text{ t} = 1.07 \times 10^6 \text{ t}$$

The latter figure thus corresponds to our minimum estimate for the amount of magnetite discharged to the sea in Portman from 1957 to 1990. However, given that in those years the steel industry gave priority to concentrate grade, SMMPE put more emphasis on Fe grade than anything else; thus, the recovery of magnetite may have been in the order of 50 % only of the total contained magnetite:

$$\text{TMC}_{\text{recovery}50\%} = 41 \text{ Mt} / (33 \times 0.5) = 2,484,848.48 \text{ t} = 2.48 \text{ Mt}$$

If we subtract from this figure the magnetite that was actually recovered during the process (167,270 t), we then obtain the figure of 2,317,578 t = 2.32 Mt. In this case, the resource estimation for Portman could be as high as 2.32×10^6 t of magnetite. In our opinion, the actual figure may be closer to the latter estimate. This would correspond to a magnetite content in the tailings of about

$$\text{Mean Magnetite Ore Grade} = \frac{\text{Total Contained Magnetite}}{\text{Total Tailings Tonnage}}$$

$$\text{Mean Magnetite Ore Grade} = 2.32 / 56.23 = 4.1 \%$$

Table 1 Production figures for the time span 1960–1966, involving the concentration works at the Roberto froth flotation plant and magnetic separation of the iron ore from the tailings

Year	Head (10 ³ t)	Galena (10 ³ t)	Sphalerite (10 ³ t)	Pyrite (10 ³ t)	Total (GSP) (10 ³ t)	Tailings (10 ³ t)	Magnetite (10 ³ t)	Fe (wt%)	Magnetite (wt%)
1960	590	10.8	7.6	10.4	28.9	<i>561.1</i>	<i>8.8</i>	<i>56.5</i>	<i>63.8</i>
1961	686	12.3	8.1	6.2	26.7	<i>659.4</i>	<i>15.8</i>	<i>58.0</i>	<i>41.7</i>
1962	743	13.7	7.5	5.0	26.3	<i>716.7</i>	<i>20.4</i>	<i>57.7</i>	<i>35.1</i>
1963	760	13.5	9.0	1.1	23.6	<i>736.4</i>	<i>33.7</i>	<i>57.9</i>	<i>21.9</i>
1964	804	15.4	7.1		22.5	<i>781.5</i>	<i>25.8</i>	<i>57.2</i>	<i>30.3</i>
1965	826	14.0	5.8		19.8	<i>806.2</i>	<i>27.1</i>	<i>57.6</i>	<i>29.7</i>
1966	968	16.5	8.5		25.0	<i>943.0</i>	<i>26.1</i>	<i>57.1</i>	<i>36.1</i>
Total	5,377	96.2	53.6	22.7	172.8	5,204.3	157.7	57.4 ^a	33.0 ^b

Italicized values in the table indicate data relevant to magnetite concentrates and iron ore in the tailings

GSP galena + sphalerite + pyrite

^a Mean content for 1960–1966

^b Tailings/magnetite

Bay infill

The whole landscape evolution of Portman Bay can be regarded as similar to what is observed in a typical case of downstream sediment infilling process taking place within an estuarine scenario (e.g., Bird 2008), only that in this case, there was no river but a pipeline.

After the tailings discharge to the sea, these materials were subjected to the action of the waves and currents that transported and sorted the tailings, both along the coastal shelf, and within the bay. According to Pauc and Thibault (1976), the Portman coastal currents change from winter to summer, depending on the prevailing wind conditions (Fig. 2a). During summer, the system is governed by drift currents with clockwise motion, entering the bay from the southwest and exiting the place to the southeast. During winter, the drift currents have a more complex behavior: counterclockwise-moving currents exit the bay by the southwest, while other currents move from west to east without entering the bay. As a result of this complexity and the system energy (derived from the bay bathymetry), the infilling began in the western flank of the bay. Aerial photograph series taken during the 1970s reveal that sedimentation began on the western flank (including the fishing harbor) (Fig. 2b, c) along successive SW-NE arcuate bands, eventually progressing from there towards east, which spatially coincides with magnetic gradients in the area (Peña et al. 2013). This allows interpretation in terms of alternating bands of magnetic black sands and yellowish bands rich in sulfates and clays. At present, the clockwise system of currents erodes the southwest flank, and infilling occurs in the northeast.

By the time the Roberto plant became decommissioned in 1990, the bay had already disappeared, and the tailings were

behaving as typical sediments in the near-shore environment, involving remobilization and reclassification (Fig. 2b). As a consequence of these sedimentary processes, a new large beach composed of dark sands formed (Fig. 2c). Needless to say that given the lower specific weight, the clays and sulfates (yellowish facies) were wiped out from the sea front. On the other hand, the tidal waves induced layering of fine iron ore sands and coarse quartz-rich sands (Figs. 2d and 3a).

The iron resource hosted by the Portman Bay black sands

The black sands of the actual Portman beach have been studied by this team from a double perspective. On one hand, the early works were done on the primary and oxide mineral assemblages from the manto deposits (e.g., López García et al. 1988; Manteca and Ovejero 1992); on the other hand, specific mineralogical and geochemical works were carried out at Portman Bay in recent time and for environmental purposes (e.g., Oyarzun et al. 2013). Put together the data gathered allow for a first approach towards characterization of this resource, representing about 1/6 of the total Portman Bay iron resource. This figure is an estimation based on the visible part of the resource, i.e., those materials present along the frontal part of the beach. The inner part of the resource is covered by either vegetation or hardpan-type crusts.

This work may be regarded as preliminary, but it is the only one involving the different aspects of a complex history in a holistic view: characterization of the primary ores at the mantos, an account of the metallurgical procedures that eventually led to concentration of the iron ore, and, last but not

Fig. 2 (A) Sea currents and wind patterns during summer and winter at Portman Bay (after Pauc and Thibault 1976). (B) Portman Bay variation in bathymetry through the years (after Martínez et al. 1993). (C) The

present (ex) Portman Bay (Google Earth image). (D) Schematic N-S cross section in the bay of Portman, depicting main old and present features and position of iron ore bodies

least, an in situ study along the Portman beach to collect samples by trenching and pitting. We separated granulometric fractions and the corresponding magnetic fractions using a Frantz instrument. We also did X-ray diffraction (XRD) studies and studied polished thin sections and blocks.

The beach samples are rich or extremely rich in metals and metalloids, a fact that should be taken into account in any major bulk earthmoving works at Portman, either for mining or environmental purposes (Oyarzun et al. 2013). To assess metal and metalloid contents in the sands, we did a geochemical sampling transect along the beach (~900 m), excavating eight pits of about 0.5 m deep and 0.3–0.5 m wide, from where 3 kg of bulk samples were taken (Carmona 2012). These samples were analyzed at the Almadén School of Mines, Geochemical Laboratory, by XRF. We found the following mean contents ($n=8$): Fe (40.5 %), Pb (0.27 %), Zn (0.72 %), Cu (98 ppm), As (559 ppm), Cd (63 ppm), and Hg (39 ppm). The low Cu contents were expected in a district dominated by a Pb–Zn signature, whereas the As concentrations are related to the presence of arsenopyrite. The presence of mercury might be due either to the existence of minor tetrahedrite in the MP-1 paragenesis

or to industrial pollution. Besides, in order to assess the magnetite contents, we did magnetic separation in six samples using a Frantz instrument at the Faculty of Geological Sciences (Universidad Complutense). In turn, the magnetic fractions were studied by XRD and reflected light microscopy. The magnetic fraction has a mean weight proportion ($n=6$) of 23 % of the bulk sample, thus implying that the magnetite is associated with other (nonmagnetic) Fe mineral phases. This relationship is well depicted in Fig. 3b, which shows why the actual Fe content is much higher than it would be expected if all the ore were “pure” magnetite (see also Fig. 3c, d). In fact, this is a major factor to be carefully considered in any potential mining operation at Portman: as observed in MP-2 ore samples, magnetite is finely intergrown with hematite and siderite (Fig. 3c, d). According to Oen et al. (1975), magnetite formed during the late stage of this paragenesis, by replacement of siderite and hematite, which explains the complex intergrowths between these minerals. Given that magnetite concentrates in the finer fraction (Fig. 3a), and the three Fe mineral phases are intimately intergrown, complete liberation might be difficult to achieve (Fig. 3c, d). In

Fig. 3 A sampling pit at Portman bay. **a** Centimetric to millimetric scale layering of coarse and fine (Fe minerals bearing) sands; a relict sulfate crust can be observed at the top. **b** Stoichiometric magnetite composition (1) compared to the actual “iron ore” from Portman Bay (2); note the remarkable Fe enrichment in (2) as a result of the presence of complex magnetite ± hematite ± siderite grains in the sand samples. **c–d** Intergrown Fe mineral phases under the microscope; *FeSil*, greenalite; *Hem*, hematite; *Mgt*, magnetite; *Sid*, siderite

this regard, if we do not take into account the very minor mineral phases (e.g., galena, sphalerite, etc.), the mineralogical composition of the beach iron resource is (very small amounts of other minerals are not included here in this “mean” composition) the following: quartz (17.3 %), magnetite (35.1 %), siderite (35.5 %), and hematite (12.1 %).

Conclusions

The Portman Bay hosts an unusual type of iron ore resource formed by beach placers of anthropogenic origin. Decades of tailings disposal onto the sea near to the beach together with the action of tidal waves and sea currents resulted in large concentrations of magnetite. This mineral fraction is intergrown with hematite and siderite and associated to the fine sand fraction. The origin of magnetite and siderite is the primary ores of manto-type mineralization in the Sierra de Cartagena-La Unión district. The ore was milled and went to the tailings dump after galena and sphalerite extraction at the Roberto froth flotation plant (Portman).

The Roberto froth flotation plant disposed 56.23 Mt of tailings (1957–1990) directly to the sea. Unfortunately, the sea current system dragged this material back to the bay. Moreover, these sea currents also contributed to the mechanical concentration of the magnetite ore, eventually forming the Portman Bay iron resource. The frontal beach resource (1/6 of the total potential resource) can be estimated at $700 \times 10^3 \text{ m}^3$ ($\sim 2.3 \text{ Mt}$ of black sands). This could yield $444 \times 10^3 \text{ t}$ of magnetic iron concentrate at about 51 % Fe. Special attention should be paid to the high metal contents of these sands, with Pb and Zn mean contents of 0.27 and 0.72 %, respectively, and elevated As, Cd, and Hg contents. Given that the thickness of natural beach placers rarely exceeds 3 m (Smirnov 1976), the Portman black sands with a combined thickness of about 10 m (Martínez Sánchez et al. 2008) can be regarded as a large deposit (Fig. 2d).

Acknowledgments We would like to thank María José Martínez Sánchez and Carmen Perez Sirvent (Research Group E08-48 on Soil Contamination) from the University of Murcia for helpful information on the Portman Bay. Pablo Higuera and José María Esbri (UCLM) are thanked for the analytical work on the Portman samples. Bernd Lehman (Editor) is thanked for his review and useful comments on the manuscript.

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